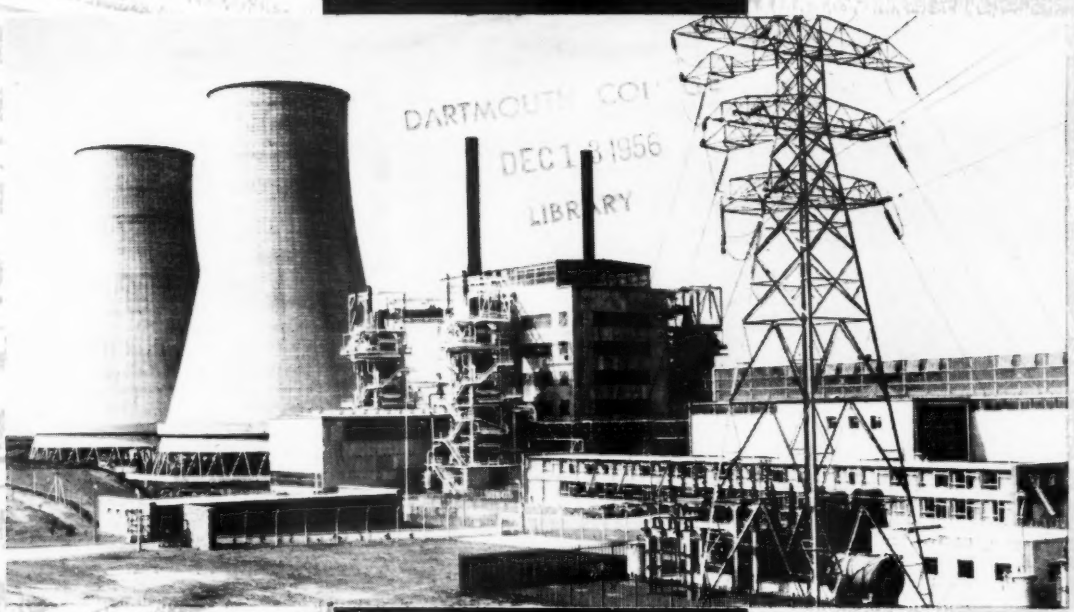
Nuclear Power

The journal of British nuclear engineering

I.C.I. Tubes & Plates at Calder Hall



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In addition to 104 tons of condenser tubes, I.C.I. supplied Messrs. C. A. Parsons & Co. Ltd., makers of the turbo-generating and condensing plant, with all the plates (134 tons) for main and dump condensers.

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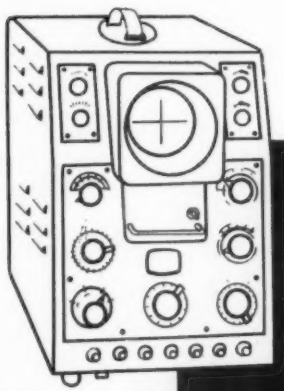
Cossor Oscillographs in research



The value of the Cathode Ray Oscillograph as an aid to scientific investigation is so high and so widely appreciated that further emphasis on its importance is unnecessary. We *would* emphasise, however, that Cossor Instruments Ltd., in providing a wide range of these invaluable instruments, have been able to help Research with the solution of many of its difficult problems and are anxious to place their long experience of the subject at the disposal of enquirers.

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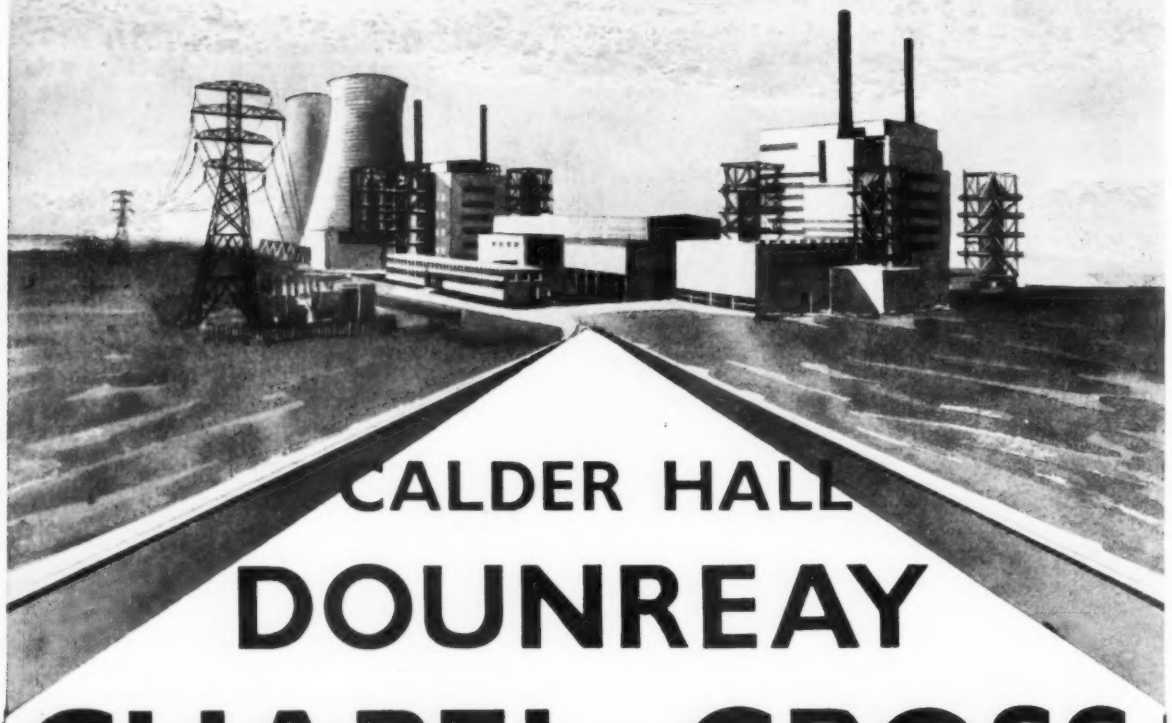

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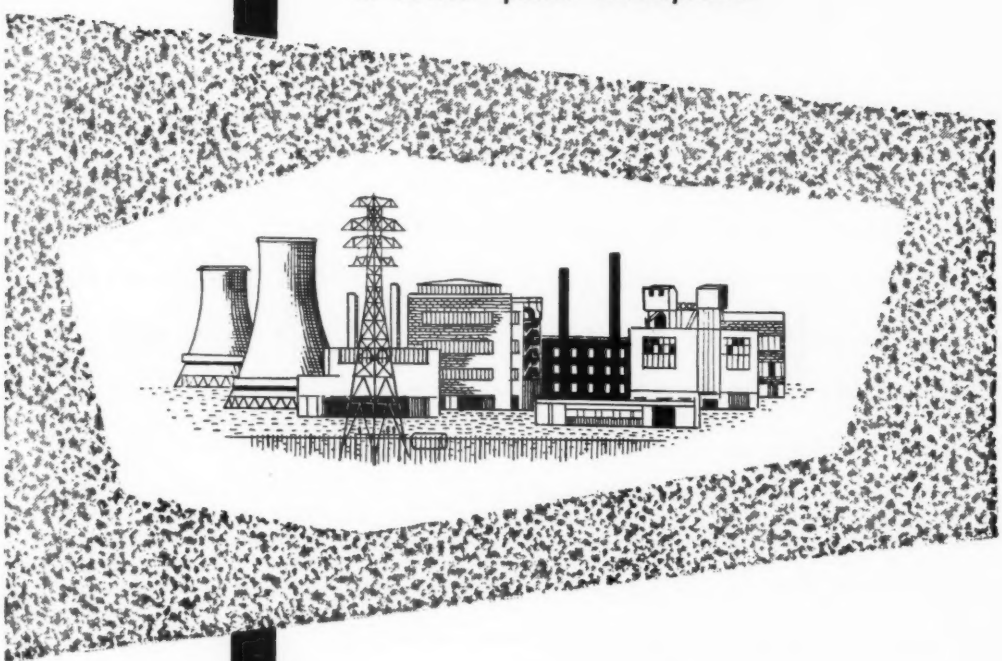

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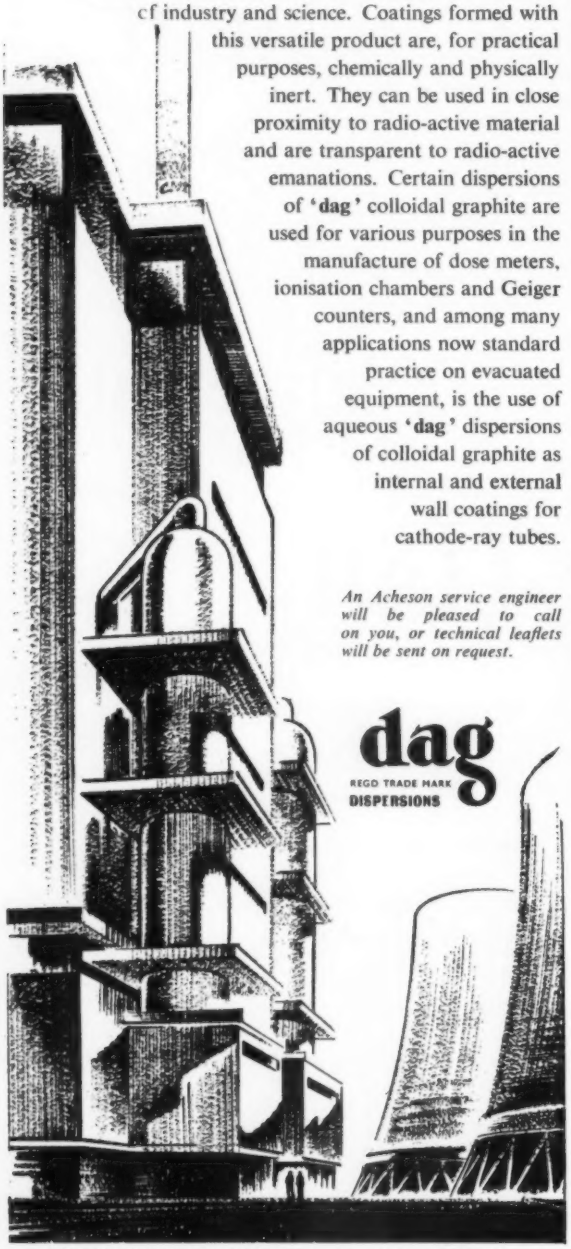

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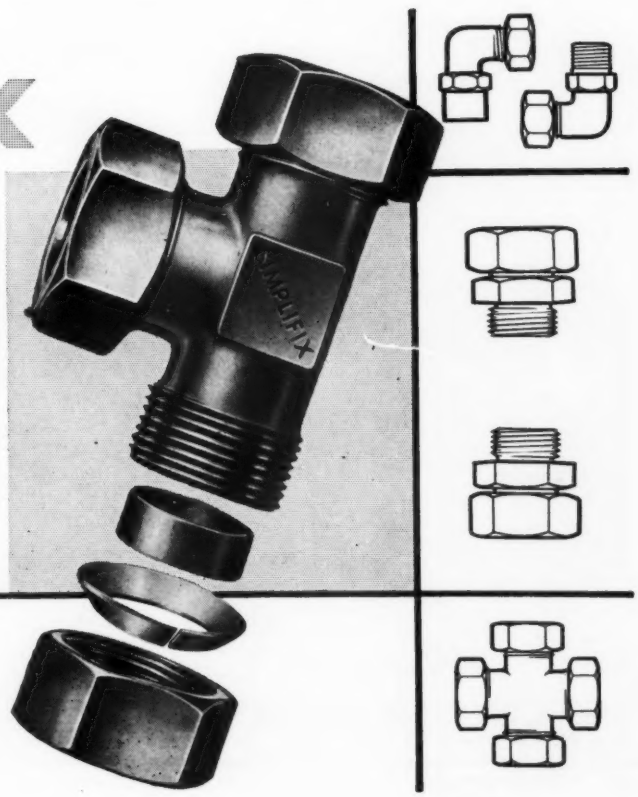

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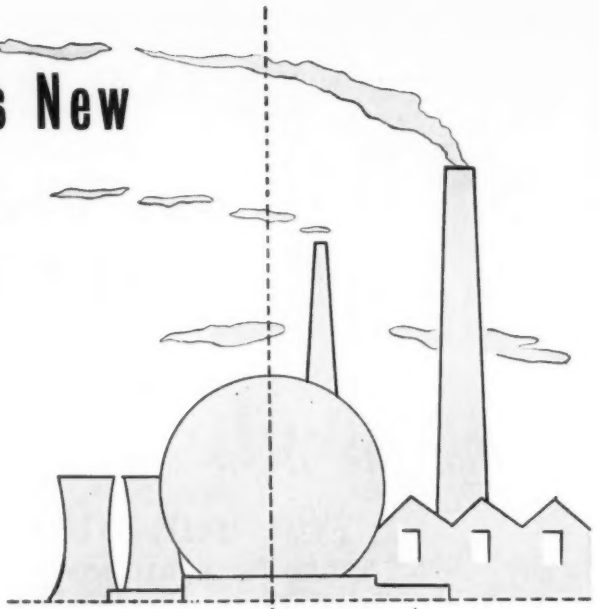

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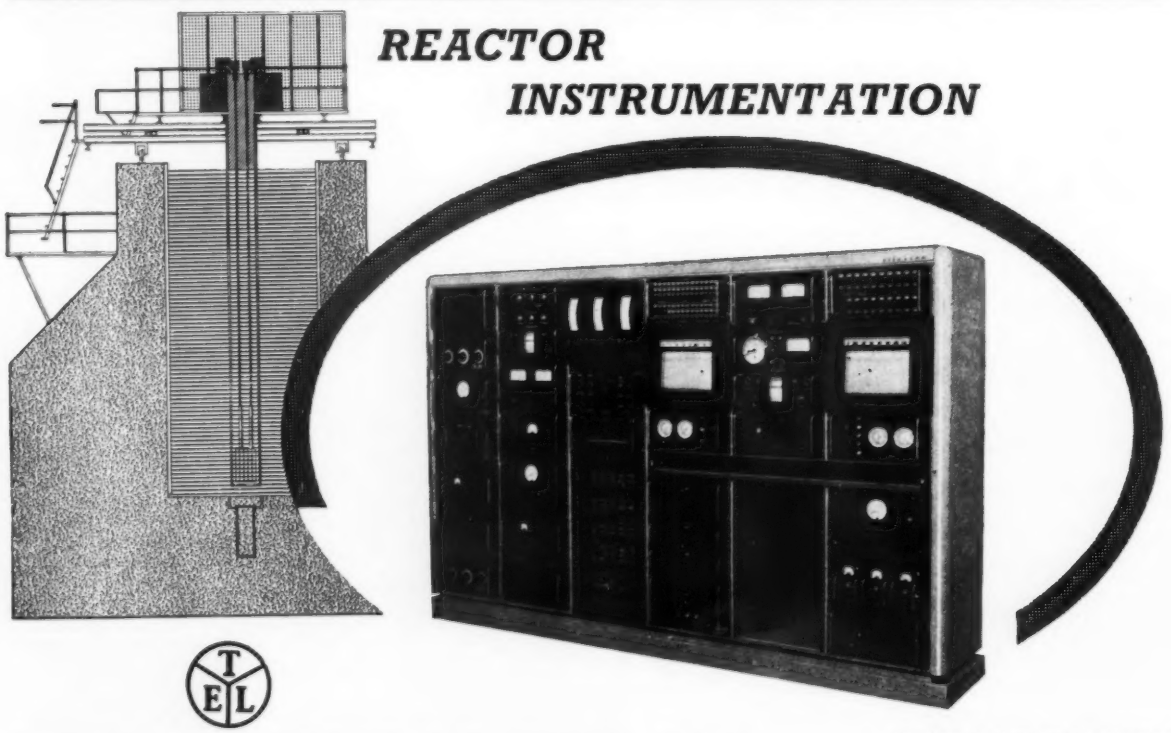

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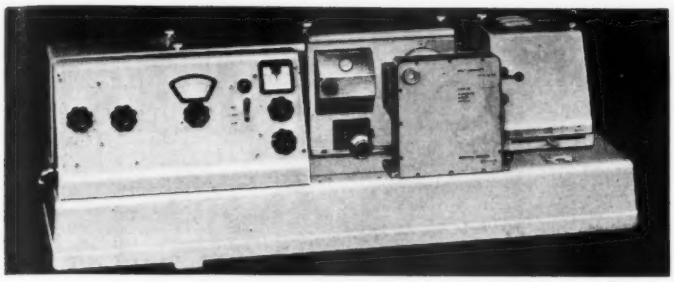

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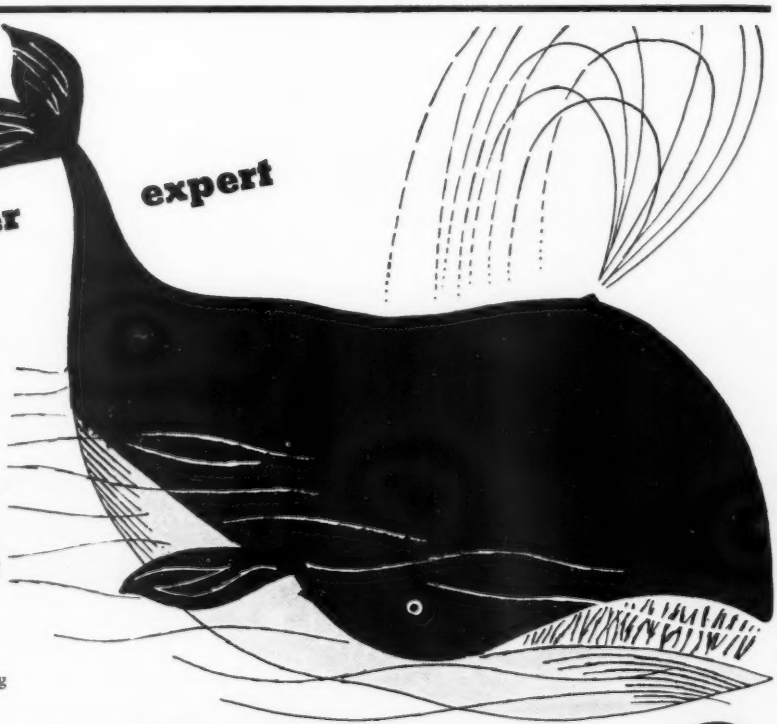

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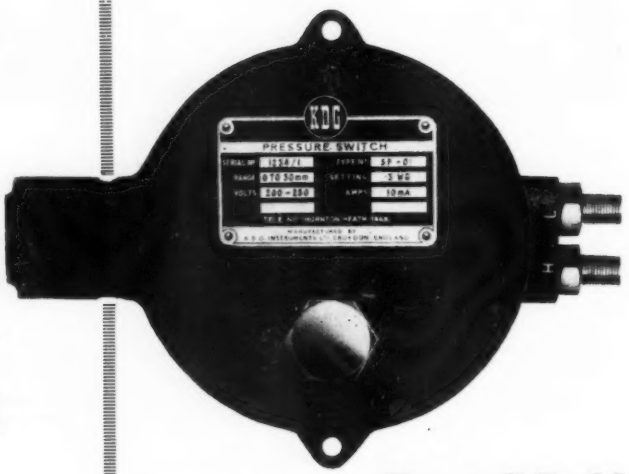

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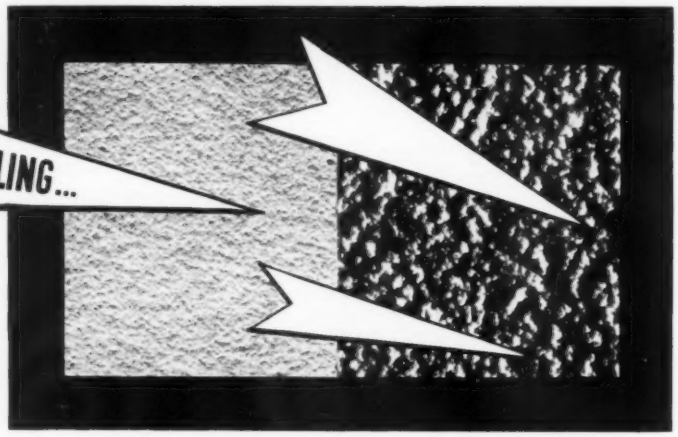

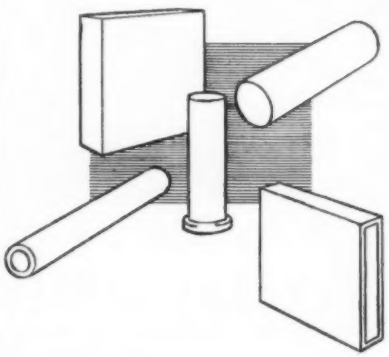

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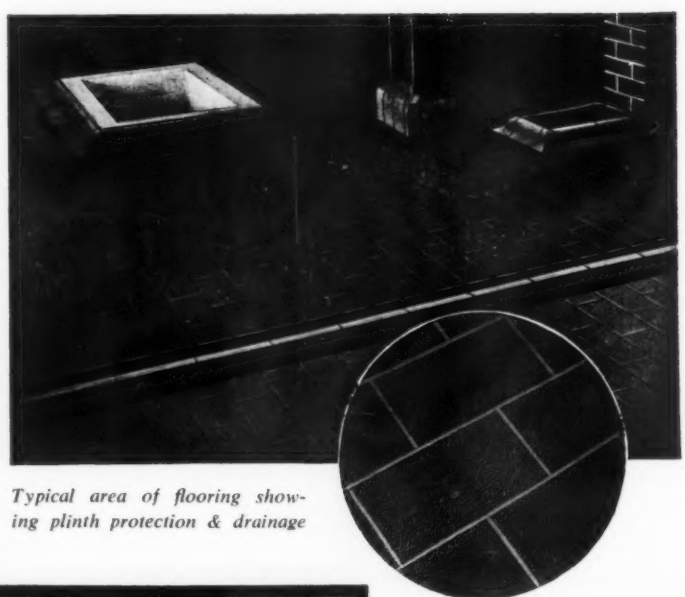

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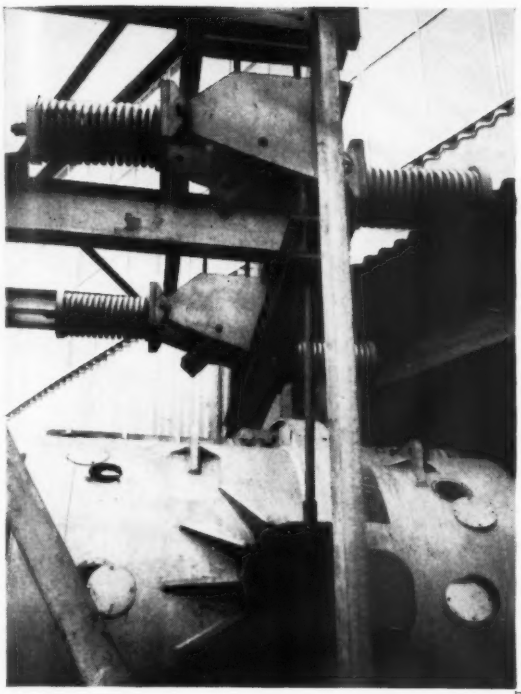

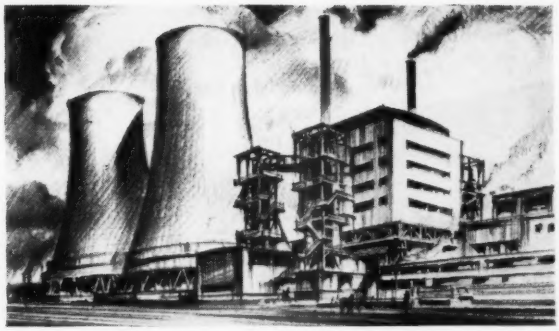

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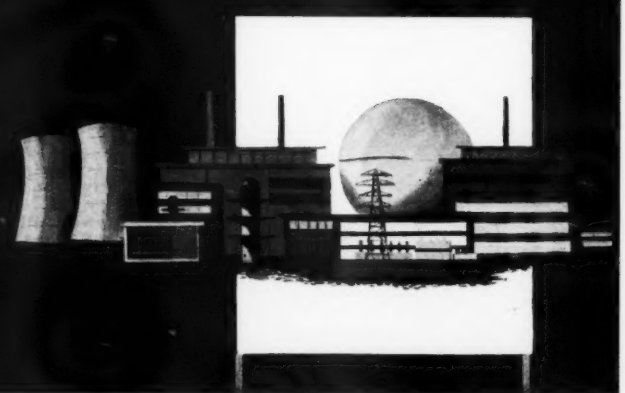

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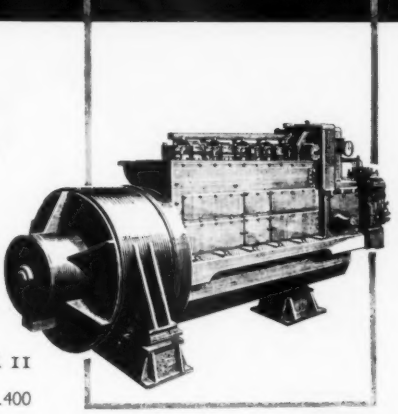

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DELAY REPETITION RATE: 0-400 kc.
OUTPUT IMPEDANCE: 0-600 ohms.

This is a large instrument, and it is supplied complete with its necessary power supply (not illustrated), arranged at choice for bench or rack operation. The Generator proper has thirty-six vacuum tubes. Considering its flexibility and completeness the price is reasonable —£1,047 net delivered (U.K. only). For complete data see the 13-Page article in "GENERAL RADIO EXPERIMENTER" for May 1956, (Vol. 30, No. 12) or request the latest "G.R." Catalogue '0' Send your written application to our nearest address, please.

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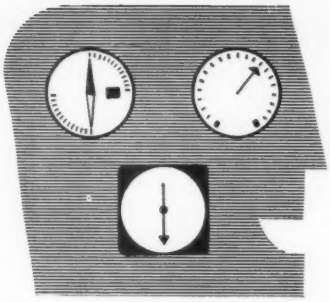
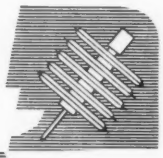
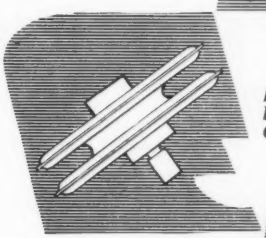
VACUUM AND PRESSURE MEASUREMENT

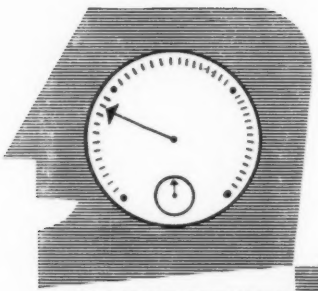


POSITION INDICATORS FOR ANGULAR AND LINEAR DISPLACEMENTS

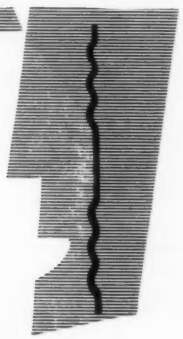


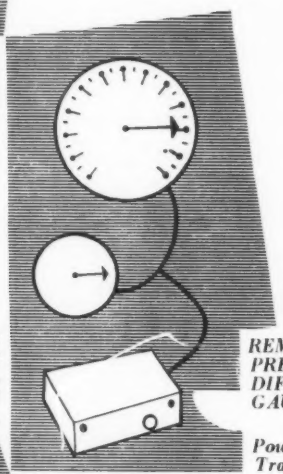


PRESSURE RESPONSIVE ELEMENTS in Beryllium Copper, all joints hard soldered.



INDICATING PRESSURE SWITCH with indicating switch adjustment.





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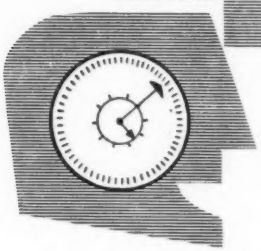

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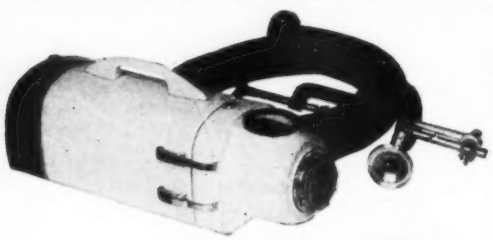

Radio-active Dust Sampling Equipment

Developed in collaboration with
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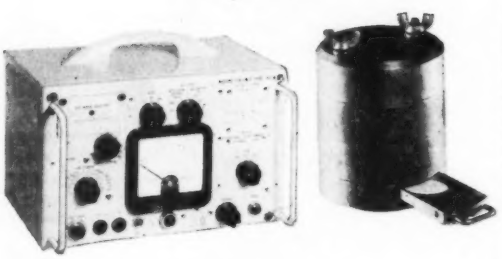

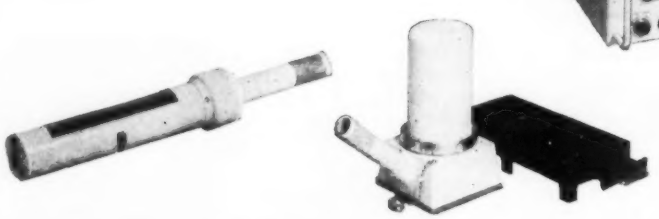

This group of instruments forms a universal dust, personnel, and area monitoring equipment for alpha, beta, or gamma contamination. Whilst the various units have been designed to work together as a whole, they may be used individually for general works or laboratory purposes.

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Type 40	**Miniature Amplifier**	Gain 100; bandwidth 15 c/s–10 Mc/s; stepped gain control.
PE31FD	**(Mk 2) Tapped Delay**	15 Mc/s rise time delay line between cathode followers, Delays ·05, ·1, ·2, ·5 microseconds.
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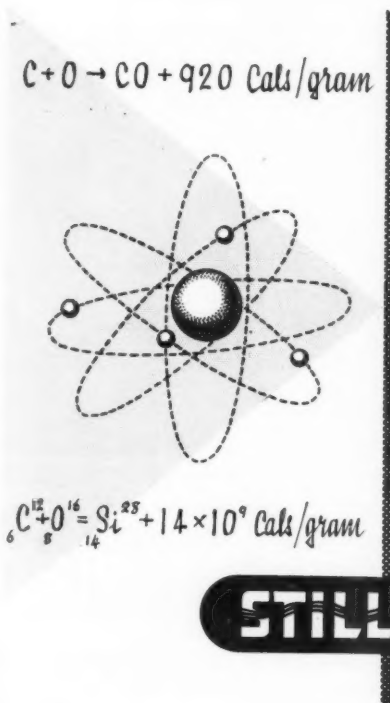

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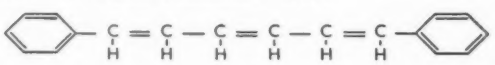

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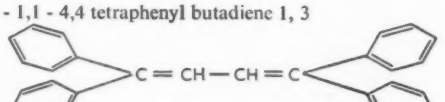

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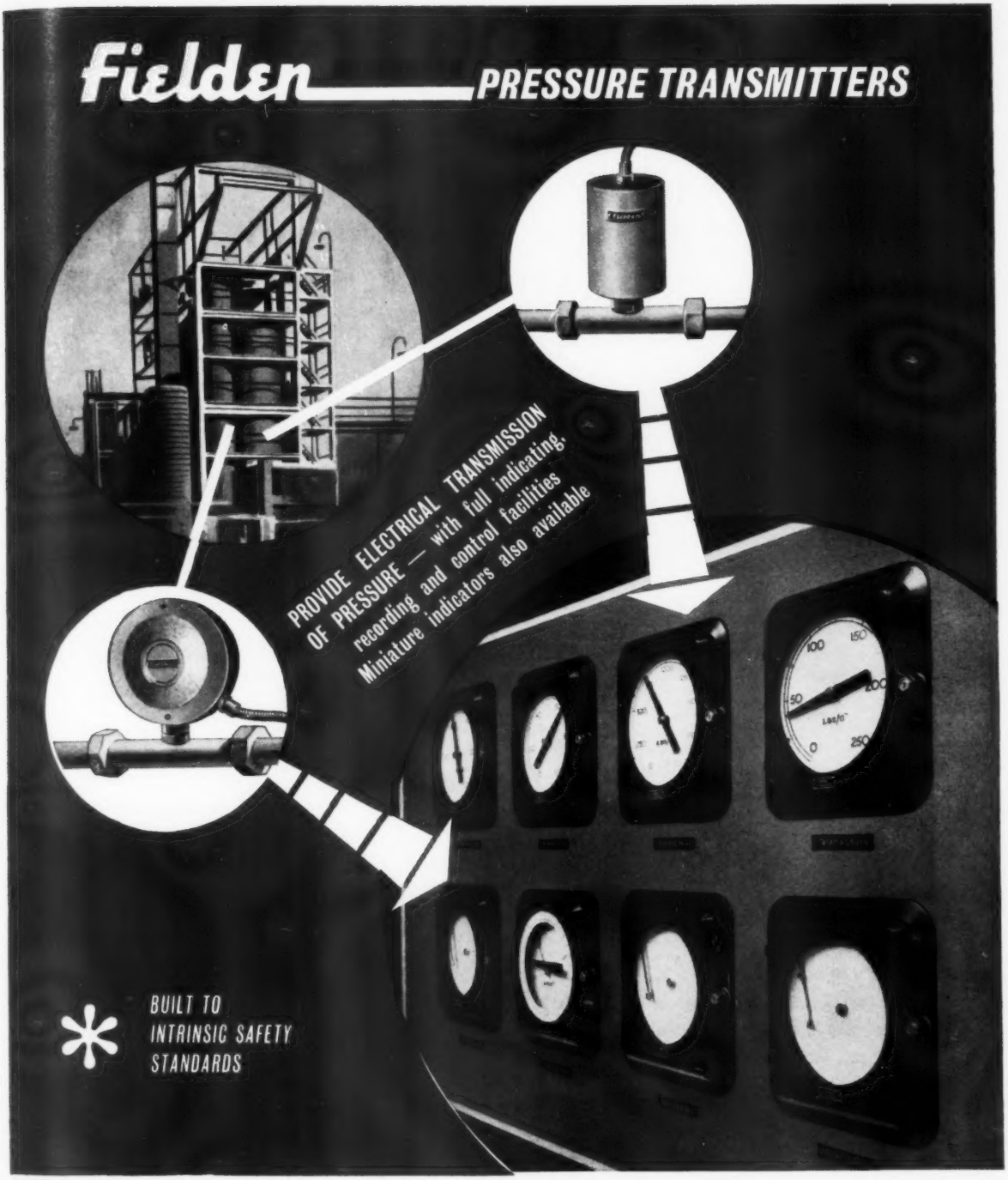
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Fielden AUTOMATION

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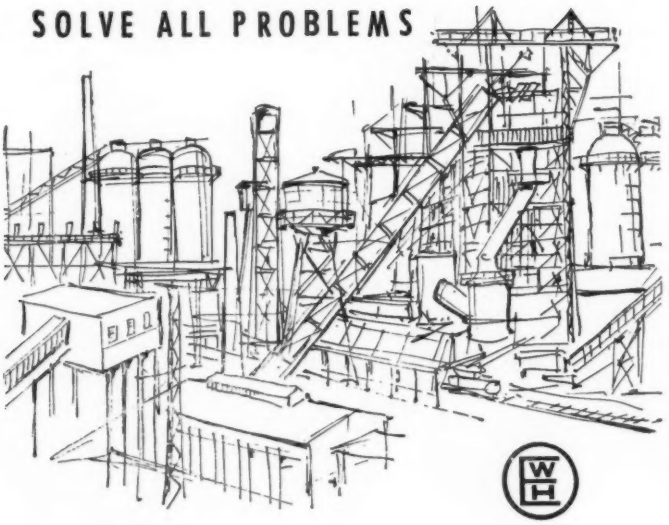

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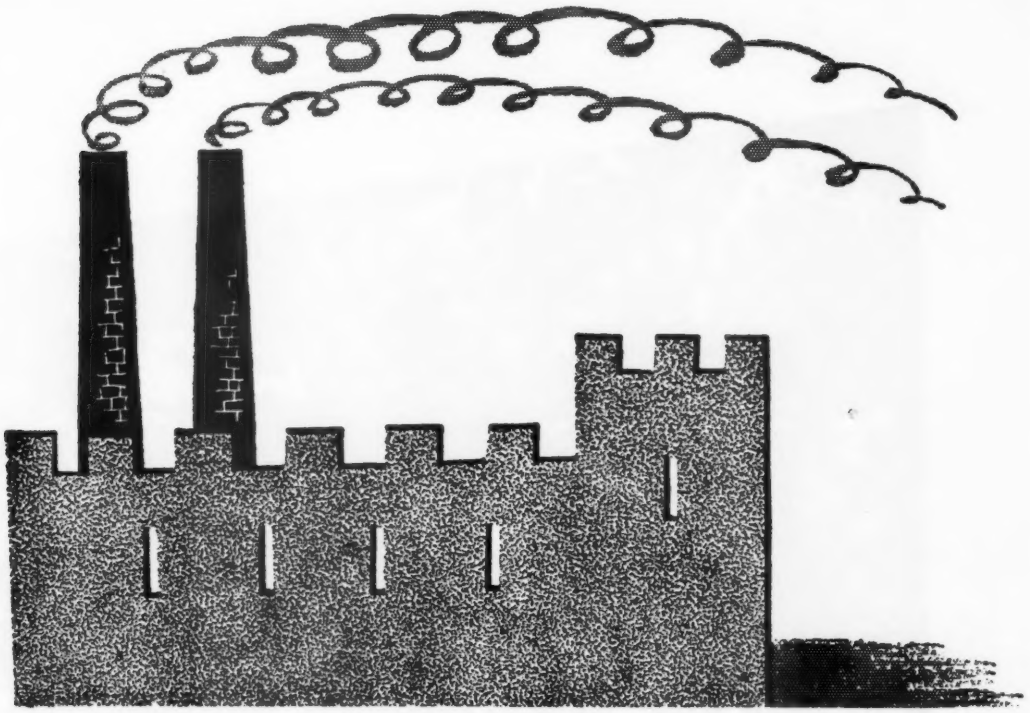

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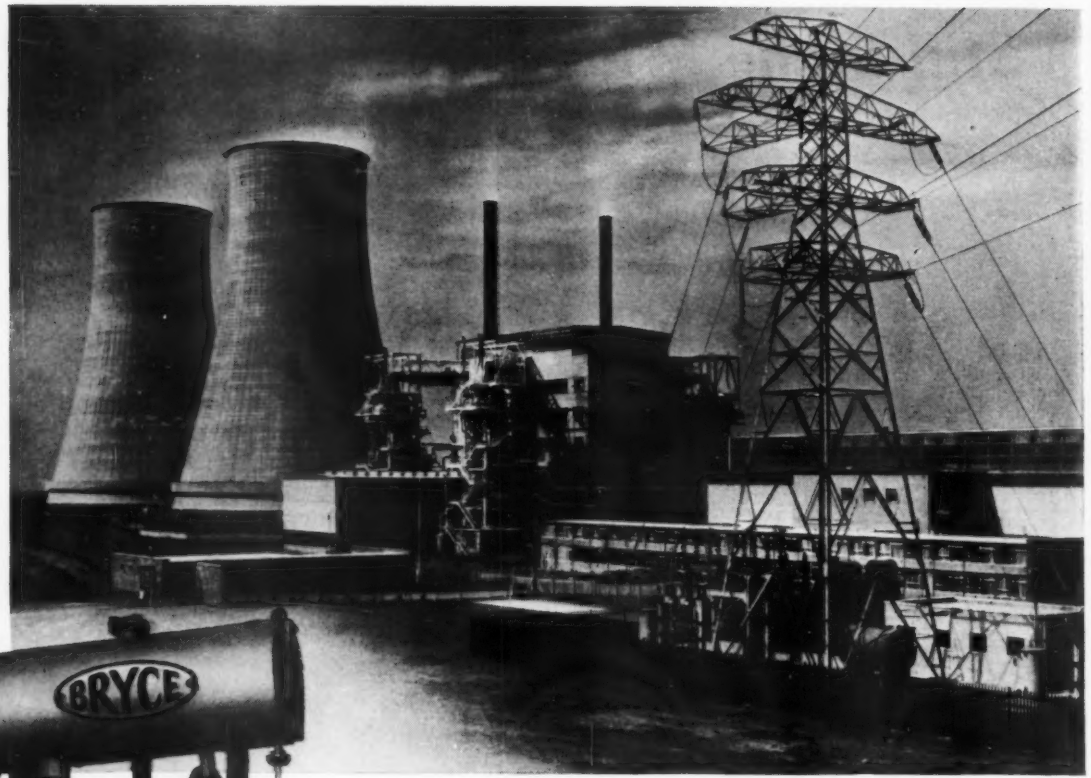

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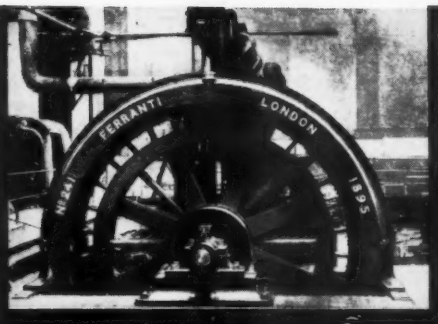

1895

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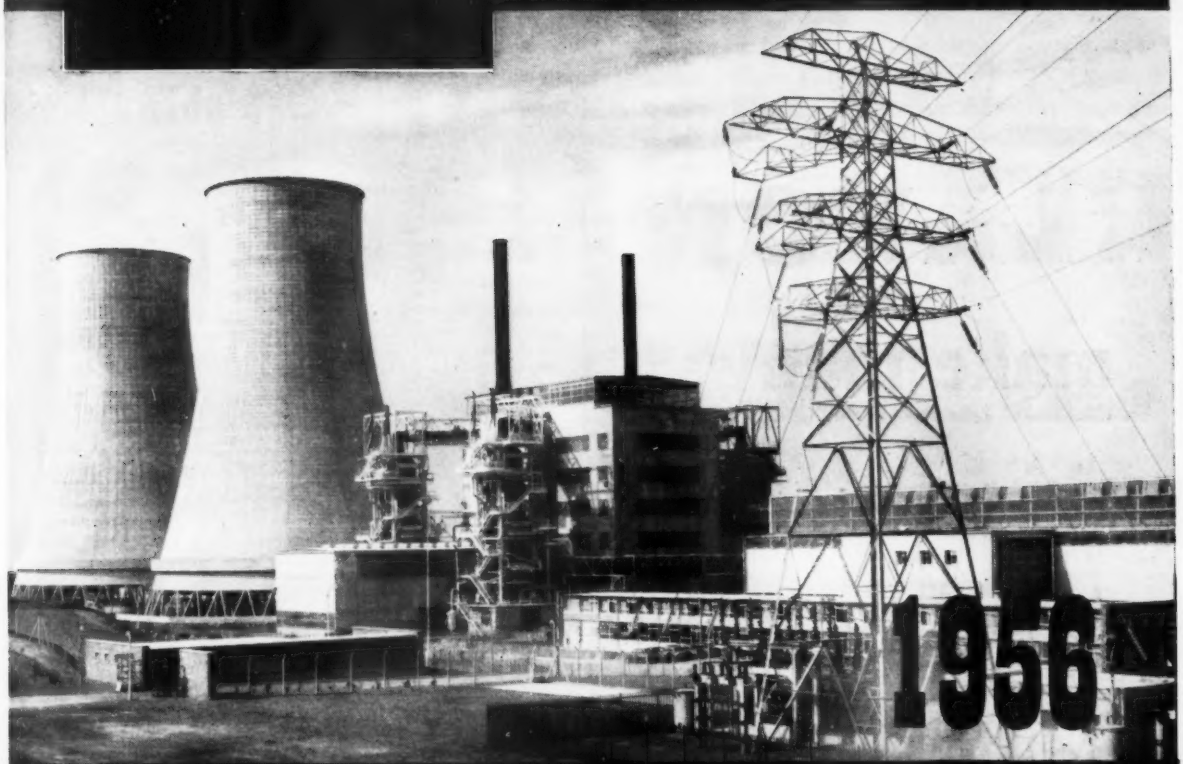

1956

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The Electrical Insulation People

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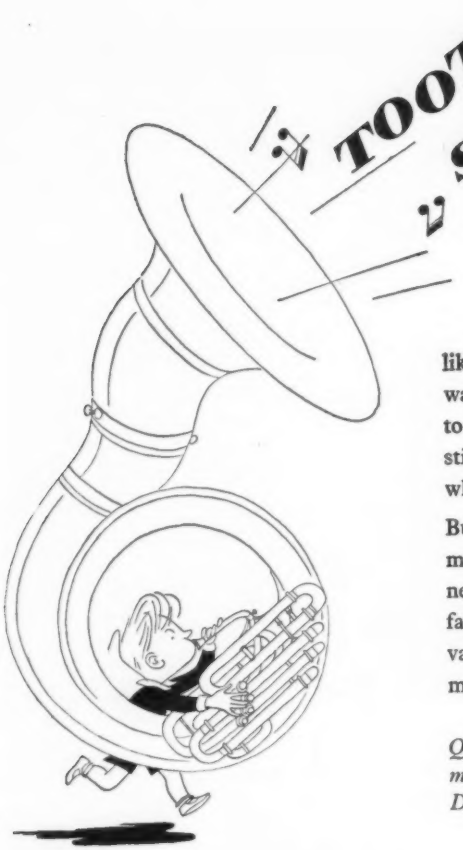

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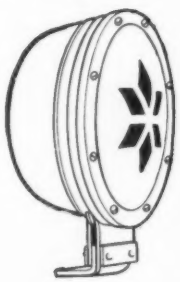

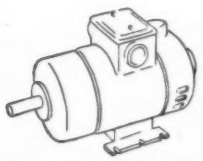

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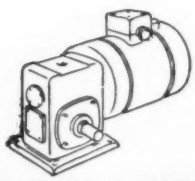

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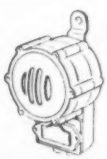

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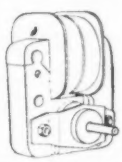

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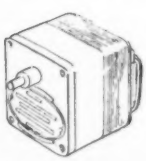

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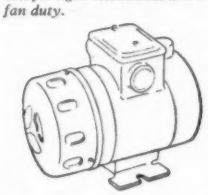

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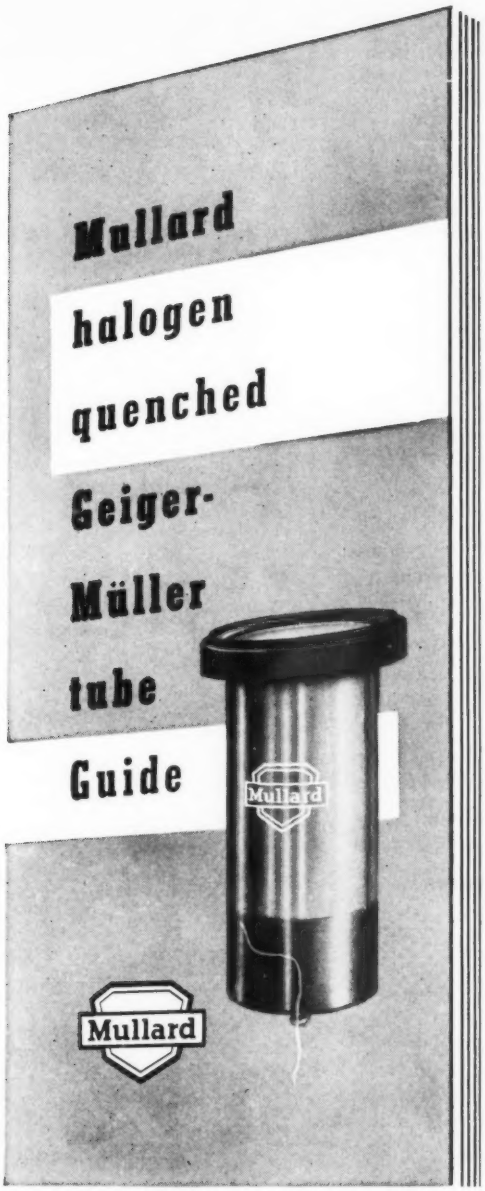

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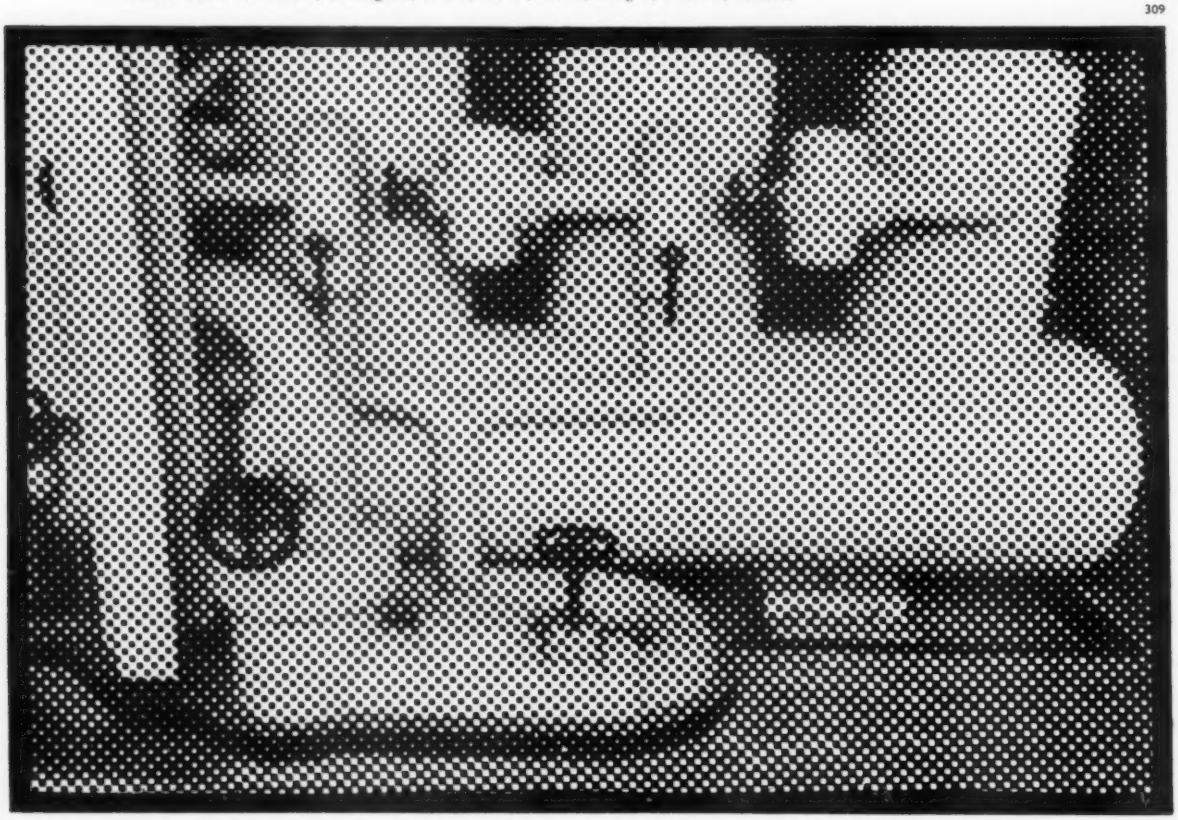

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SPECIAL CALDER nos

As a fitting climax to NUCLEAR POWER'S coverage of Britain's first power station, this month's issue is devoted almost entirely to the symposium on the plant held last month by the British Nuclear Energy Conference

December 1956

Volume I

Number VIII

Nuclear Power

The journal of British nuclear engineering

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Nuclear power for the nation's future

AN EXAMPLE of industry pooling its resources to prepare for a mighty project is the linking of the A.E.I.—John Thompson Nuclear Energy Company with two important firms of Civil Engineering Contractors—Balfour Beatty and Co. Ltd., and John Laing and Son Ltd.

To the strength of the A.E.I.—John Thompson Nuclear Energy Company and its constituents (British Thomson-Houston, Metropolitan-Vickers and John Thompson) is added a fund of knowledge in the civil engineering field.

The Balfour Beatty Group has a world-wide reputation in all forms of engineering and construction work and is at present carrying out major contracts for the Central Electricity Authority.

John Laing and Son Ltd. has carried out building and civil engineering work at the first Government Atomic Energy Establishment at Windscale and is at present engaged in the construction of power stations in the United Kingdom, as well as in major development schemes in Canada.

RADBROKE HALL · KNUTSFORD · CHESHIRE

Nuclear Power
DECEMBER 1956 VOLUME I NUMBER VIII

In business!

THE NEWS that a UK firm has secured the pressure vessel contract for the NPD pressurized heavy water reactor in Canada is of more than passing interest. It shows that the basis of a heavy nuclear industry is established in Britain and that the world is already prepared to come to us, not only for specialized laboratory equipment but also for large capital plant items. Benefiting from the inestimably valuable experience of building Calder Hall under the tutelage of the Atomic Energy Authority, the British nuclear industry is now standing on its own feet and has opened shop. Just how far it has developed is not easy to gauge at the moment, since much of the merchandise is still under the counter, but an order like this gives some indication of the confidence which overseas countries are now prepared to place in us. Soon, as the successful CEA tenders are announced, the posters will be going up and it is hoped that the Japanese mission recently in this country will be one of the first foreign customers for a pippa-type reactor from one of the big British groups.

Another indication of the rapid expansion of that section of British industry able to offer complete power stations are the facts that a fifth large contracting group has been formed and that at least two further combinations of boilermaker and electrical engineer are in advanced states of preparation. There will be a certain amount of ephemeral prestige attached to the first contracts to be awarded but let there be no mistake: it is going to need all the productive resources at our command to carry out the doubled-up White Paper Plan, details of which are expected shortly.

In an age of rapidly changing patterns in industry, the arrival of nuclear power will mean another tremendous industrial switchover, comparable with the change in the aircraft industry from piston engines to turbines, or with the advent of automation in production engineering. In ten years' time, it is unlikely that we will be building any more conventional boiler plant for central power stations in this country. This might have been bad news for the boilermakers were it not for the fact that these companies are precisely the ones which will be called upon to lead the building of the new-type power stations. Their basic trades of pressure shells, manifolds and pipework will stand them in good stead, but in place of p.f. and oil burners, pulverizing mills, fuel, ash and dust handling plant, they will have to learn the technologies of nuclear fuel elements, charging and discharging equipment, control mechanisms, fuel reprocessing plants and a host of other exotic sidelines. In this they will need—and be sure of—the assistance of wide sectors of satellite industries.

The NPD contract also shows that, far from being wedded to the pippa-type reactor, British industry is now looking further afield to a stage where a much greater variety of reactor is possible, and it is clear that our industrial tradition is beginning to assert itself once more. Atomic energy has, however, no tradition yet and a period—perhaps a difficult one—of formation and assimilation lies ahead.

Nuclear power developments in this country, it is clear, cannot be allowed complete freedom of action: they must be carried out under and orderly integrated plan. For example: the numbers of the different possible types of reactor must be controlled so that the maximum possible utilization of fuel is obtained. Theoretically this could be done merely by the electricity undertakings—by far the largest potential customers in the foreseeable future—specifying the correct types to give a balanced fuel economy. This would normally be done in cooperation with the AEA but these bodies have no monopoly of talent and there is a grave danger that this could lead to a stifling of initiative and a sense of frustration in industry. Consultations with industry would probably take place but this is not enough.

The problem is not a new one and is commonly met with in mixed economies like ours. It is: how to ensure a fair deal for industry, at the same time ensuring that its efforts are directed to the benefit of the nation. The solution is not simple but it must obviously include both freedom and direction. Firms should be encouraged to play a positive part by using their initiative to develop completely new types of reactor, yet they cannot be allowed to build them until they have been approved as being both safe in operation and practical from a fuel point of view. This, it will be noted, is not so very different from the situation in the United States—a country noted for its anathema to anything savouring of Government interference.

In this new type of industrial organization the AEA will have a most important part to play. It will act as a guide, philosopher and friend to this lusty young industry and so help to rear it through its formative years.

Reactor Instrumentation

Ekco Electronics have made vital contributions to the instrumentation of the existing reactors at Harwell and Calder Hall, and are responsible for the nucleonic instrumentation of the reactors under construction in Australia, and at Harwell and Dounreay. This marks yet another important step in the long line of Ekco achievements in nucleonic measurement—a field in which we were pioneers and in which we continue to lead.

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UNITED KINGDOM

British LMFR proposed

A British company has announced plans to build a liquid-metal fuelled reactor. This was disclosed on November 5 by Hawker Siddeley chief Sir Frank Spriggs on his return from a visit to Canada. Sir Frank said the Hawker Siddeley Nuclear Power Company, which was formed earlier this year, had started work on the LMFR at its Langley, Bucks design and development centre. There, the company have a first class design team and, as a first stage in a far reaching experimental programme, a well-equipped metallurgical laboratory is nearing completion.

Sir Frank went on: 'We are interested in the development of advanced reactors for electricity generation because it seems to us to open up vast export possibilities for British design genius by providing easily transportable, small reactors to countries which will not be able to build their own for a long time to come. The lead which we are gaining in the development of nuclear power means that Britain is right in the forefront of the new industrial revolution, as she was in the first one, and will once again play a major role in raising living standards all over the world.'

Mr E. P. Hawthorne, 36-year-old chief executive of Hawker Siddeley added: 'metallurgy is the starting point for any development towards higher temperatures in nuclear reactors and we are actively engaged in an ever-increasing programme.' Although the company were naturally interested in the aircraft problem it was certainly not their only objective. They saw applications of their work to packaged reactors for use in remote areas, for ships and for the production of process heat. 'The Hawker Siddeley Group,' Mr Hawthorne concluded 'is able to back its work by providing high grade engineering services and even the construction of industrial buildings. The company can, therefore, also provide specialist services to other manufacturers of nuclear equipment.'

Directors of the company, in addition to Mr Hawthorne are: Sir Roy Dobson, managing director A. V. Roe & Co Ltd; Sir Arnold Hall, technical director, Hawker Siddeley Group; Sir William Farren; technical director A. V. Roe & Co Ltd; Mr H. T. Chapman, managing director Armstrong Siddeley Motors Ltd; and Mr H. G. Herrington, managing director High Duty Alloys Ltd.

Some idea of the company's views on aircraft propulsion may perhaps be gained from Mr Hawthorne's lecture to the Royal Aeronautical Society in London on October 31. A manned atomic bomber might have a 250MW LMFR in the fuselage with jet engines at the wing tips. It would carry a payload of 4½ tons at 60,000 ft with a speed of Mach 2½. Mr Hawthorne considered such a plane 'definitely possible,' but thought that it might need the combined resources of the whole British aircraft industry.

Babcock's get NPD vessel

The Canadian pressurized heavy water power demonstration reactor, NPD, is to have a pressure vessel designed and made in Britain. A contract for the vessel worth about £270,000 has gone to Babcock and Wilcox Ltd, Renfrew, from Atomic Energy of Canada Ltd who are to build NPD at Des Joachims on the Ottawa River, not far from the Dominion's atomic research centre at Chalk River. The contract was received last June but news of it was only released last month in Glasgow when Mr W. R. Wootton, assistant manager of Babcock's nuclear energy division gave details of the order.

The vessel will be the biggest of its kind ever built in this country and possibly in the world. It will be about 12ft in internal diameter, 35ft high. The design pressure has been specified at 1,200 lb/in^2 and this requires walls 5 in. thick, increasing to 6½ in. in places. A basic requirement is full-way access to the interior so that if necessary the entire core can be removed *en bloc*. This is going to mean a total load on the closure of nearly 9,000 tons and special measures will have to be taken to provide security and pressure tightness. The head will contain numerous small openings, each with its own closure and this will complicate the design. A special closure using segmental metal packings is being developed and to prove the vessel, a half-scale model is being built which will be tested to destruction after it has been fully stress-studied by means of strain gauges. Another design feature will be the use of push-outs for welding pipe branches (see story p 342, this issue). The whole interior of the vessel will be clad with stainless steel, welded on almost all over the surface. The vessel will weigh about 210 tons, of which 70 will go into the head. It is due for delivery in July 1958.

A somewhat similar vessel was recently completed in the United States by Combustion Engineering Inc. for the AEC's power-demonstration Shippingport reactor. This is about 9ft internal diameter with walls 8½ in. thick. The top closure, which gives full-way access, is basically a normal bolted flange joint. This design was rejected by the British company because the very great concentration of metal necessary in the flanges was thought to place a low limit to the permissible rate of heating of the reactor.

It will be recalled that the contract for NPD's 20MW steam turboalternator recently went to Metropolitan-Vickers (NP, October, p 237). Thus a large proportion of the first power reactor in the Commonwealth is being manufactured in the United Kingdom.

Dorset centre chosen

The AEA have now found their second Harwell. It will be on a 700 acre site at Winfrith Heath, Dorset about 10 miles east of Dorchester. Permission to build the research station was granted on November 10 when the Dorset County Council passed by 71 votes to 16 a recommendation of the county planning committee. The project is still subject to approval by the Minister of Housing and Local Government but it is not anticipated that this will be withheld.

In its search for a suitable site, the AEA has examined over 70 sites within a radius of 100 miles of Harwell. The establishment will need 10 million gallons of water a day and this will be obtained from local rivers and wells. A staff of about 2,500 will eventually be employed there.

The purpose of the new station—it is understood it will be a Harwell outstation—is to develop prototype power reactors of various kinds. It might also be surmised that thermonuclear work will eventually be centred there.

The proposal has met with bitter local opposition at all stages, for Winfrith Heath is at present a nature reserve and figures largely in the novels of Thomas Hardy.

Fission product Cs-137 for therapy

Britain recently delivered her first caesium-137 source produced from fission products. The consignment was prepared at the Windscale works of the UKAEA and has an activity of over 1,200 curies. It went to the Royal Marsden Hospital, London which has a special therapy unit for treating deep-seated cancers, at Sutton, Surrey.

The source is in the form of a salt of caesium and is contained in a platinum

capsule 7cm long and 3cm diameter. This is protected by lead and uranium shielding weighing nearly a ton. The gamma rays are defined by a novel form of shutter composed of curved plates of tungsten alloy moving round the surface of a sphere.

The method of extraction on a large scale was devised by a team drawn from Harwell, Windscale and the Radiochemical Centre, Amersham and the process is carried out remotely in concrete hot-cells. The plant is designed to produce regular supplies and already it has demands from 20 hospitals which will take it two years to fulfill. A larger plant will be constructed later. No other country in the world is processing Cs-137 on this scale.

The source holder was designed in Prof W. V. Mayneord's Department of Physics in the Institute of Cancer Research by Dr B. M. Wheatley in association with Mr E. W. Savage of Bryant Symons and Co, London who built the apparatus.

Although the radiation from this source is not as penetrating as that from a super-voltage X-ray machine, the equipment is very much more simple. For example it needs no cooling. The original suggestion for using Cs-137 in this way came from W. S. Eastwood of Harwell's Isotope Division.

Calder has check up

On November 9 Calder Hall no 1 reactor was shut down for a routine inspection after running for five months—continuously for seven weeks. It is understood that two main points were attended to. There had always been a possibility that the lowest fuel element in the stack of six in each channel might start buckling under the weight: during the shut down, some of these were removed for inspection. Secondly, the nuclear characteristics of the core have proved better than predicted which meant that some of the outer fuel elements reached their optimum temperature before the centre ones had reached theirs, thus resulting in an imperfect heat distribution. A minor adjustment of the coolant distribution to the individual channels would presumably have been done.

The reactor was brought critical again after only nine days outage—a fact which confirms the AEA statement that it had passed the stringent examination satisfactorily.

Further shut-downs may be expected in the course of the next six months in order to gain experience of the reactor's behaviour under operating conditions. At the BNEC symposium, H. G. Davey stated that the reactor was now delivering 47·8MW at the alternators.

AEC office in London

The United States Atomic Energy Commission is to open a London office shortly, at the US Embassy, 1 Grosvenor Square, W1. In charge will be Dr E. L. Brady of Knolls Atomic Power Laboratory, Schenectady NY, whose mission will be to assist in the scientific and technical aspects of the rapidly expanding work deriving from the US 'Atoms for peace' policy. In addition, Dr Brady will deal with scientific and technical problems arising out of the US/UK bilateral agreement.

Speaking at Harwell on the occasion of the Dido opening in reply to a question, Sir John Cockcroft admitted that so far his submarine reactor team had received no US assistance. By the June 1956 amendment to the 1955 bilateral (NP, July, p 104) there was set up machinery for these exchanges of classified information but it seems that it is not yet in operation.

The AEC announcement about Dr Brady's appointment also said that a similar office was being set up in Paris under Dr Amasa S. Bishop, who has been in charge of the AEC controlled thermonuclear programme. This would seem to indicate that there has been a reorganisation in this division recently.

Dido now working

In the early hours of November 7, Harwell Director, Sir John Cockcroft inserted the last fuel element into the AERE's new research reactor Dido and thus completed the critical mass. Two weeks later, on November 21, at a ceremony attended by many guests, the President of the Royal Society, Sir Cyril Hinshelwood formally inaugurated Dido by pressing a button which caused the coarse control rods to withdraw, thus bringing the reactor up to power. Speaking afterwards, Sir Cyril congratulated Harwell in now possessing the most powerful experimental plant of its kind in Western Europe (10MW, 10^{14}n/cm^2/sec). When so many lamps were going out in Europe, the President went on, it was heartening to be switching on others which at least promise well for the more distant future. He reminded his audience of the greatest of all chain reactions—the spread of knowledge and truth. 'This derives its power from human curiosity, human invention and human desire for power in the good sense of power over Nature. It needs pure materials in the form of well-educated men of science, it is controlled by "moderators," among others by sane economic principles. But it can also be inhibited by the cadmium rods of ignorant administrators, uninformed accountants and bureaucrats, for whose progressive elimination by the reform of our educational system we must pray.'

After the ceremony in the control room, which was televised by closed circuit to the guests assembled in the active handling bay, the visitors were able to see not only Dido (NP, Aug, p 165) but also the recently-completed pool reactor Lido (NP, Oct, p 238), and Pluto which is still under construction on a site about 200 yards from Dido. Pluto is very similar to Dido in many respects and is housed in a nearly-identical building. It is due critical next year and will be used mainly for engineering and metallurgical studies in a high flux, probably using plutonium fuels.

Speaking to correspondents, Sir John Cockcroft said that Dido had cost about £1½m, plus about £70,000 for the 90% enriched uranium fuel charge and about £200,000 for the 10 tons of heavy water which had been supplied from the US. In order to handle very hot materials from Dido and Pluto, a new building is being constructed. One of Dido's features, for example, will be annual production of about 30 kilocuries of Co^{60} for use in hospitals and industry.

So great is the demand for experimental facilities in Dido—and it has nearly 50 experimental holes—that a Dido Users Association has been formed from the various Harwell departments which need them. This allocates priorities and times so that the fullest possible use is made of the reactor. An interesting research facility, which is not in operation yet, is the super chopper which will be used for measuring neutron spectra. This involves a 100-metre evacuated tube which will run out of Dido's pressure shell to a separate building.

Westgarth-Crompton link up?

A turbine for the highest pressure so far recorded in Britain is to be built at Hartlepool by Richardsons Westgarth. Supplied from a single Benson boiler, the unit will deliver 9250kW with steam conditions 3,000 lb/sq in, 1050°F. A double casing design will be used and steam will be passed out for process heating. Brown Boveri of Switzerland, with whom RW have long association, will help with the design. The set will go to the Margam B power station of the Steel Company of Wales.

Reports that Richardsons Westgarth Atomic had joined with Crompton

Parkinson to form a new group to tender for CEA nuclear power stations still remain unconfirmed at the time of writing, the firm declining to confirm or deny them, but there seems little doubt that they are substantially correct.

Japanese to buy British?

A mission from Japan recently spent nearly three weeks in Britain visiting AEA establishments and industrial firms. Headed by Mr Ichiro Ishikawa of the Japanese Atomic Energy Commission, the delegation's object was to investigate the possibility of buying a gas-cooled reactor from a British firm.

The Japanese party commenced their stay in the UK with visits to Calder Hall, Springfields, Risley and Harwell. They then visited a number of firms including GEC Simon-Carves at Erith, Mitchell Engineering Ltd, AEI—John Thompson, The Nuclear Power Plant Co, English Electric, Babcock and Wilcox and Elliott Brothers.

In a reported interview, Mr Ishikawa said Calder Hall appeared to be a better proposition than the American proposals. The US had offered an advanced reactor running on enriched fuel but it had been rejected on safety grounds. This was particularly important in countries like Japan where there was always an earthquake hazard. Conversations took place on an inter-Governmental fuel contract and Mr Ishikawa believed that, provided agreement could be reached on a few points, the British reactor would be most suitable for his country.

Members of the 10-man delegation included Dr S. Hoki, Deputy Director of the Atomic Energy Bureau and other members of the Commission and the Bureau, together with Mr A. Tsujimoto of the Tokio Electric Power Company.

AUSTRALIA

Isotope show for Sydney

Designed to demonstrate the industrial uses of radio-isotopes and to stimulate their application in Australian industry, an exhibition is to be held in Sydney from January 29 to February 2. The exhibition, which is being organised by the Australian Atomic Energy Commission, will be held in the Conference Hall of the Maritime Services Board, Circular Quay, Sydney.

Duke at Rum Jungle

In the course of his journey last month to Melbourne, the Duke of Edinburgh visited the Rum Jungle uranium properties near Darwin in the Northern Territory. Here, ore is obtained from a huge open-cast site and treated in a sulphuric acid plant. The Duke was accompanied by Minister of Supply Howard Beale, and AAEC Chairman Professor John Baxter.

FRANCE

OEEC working groups busy

The steering committee set up by the OEEC ministers in July (NP Aug, p 152) to draft a European Nuclear Energy Agency met for the first time on November 9 in Paris. The Chairman is Prof Léandre Nicolaides (Greece) and the vice-chairmen, M. Pierre Guillaumat (France) and Mr Friston C. How (UK, the Lord President's Office).

The steering committee examined the work of the various expert groups set up to study the problems and had before it the drawing up of terms of reference for the group investigating a joint chemical processing plant. It also instructed a working party to prepare a draft statute on security.

Two other groups are already at work —one under Sgr Franco Castelli (Italy) which is studying means of speeding up nuclear power station construction, and the other under Dr S. Eklund (Sweden) which is charged with visualizing a joint applied research centre equipped with research and prototype power reactors.

The Steering committee is to receive the study group reports early next year.

UNITED STATES

Einstein wrong?

A new method of releasing nuclear energy by cooling atoms is the unorthodox proposal put forward by a Dr Robert Lee Carroll, Dean of Academics and Pilot Training at the US Navy's Test Centre Patuxent R., Maryland. Speaking in a recent *Voice of America* broadcast heard in Europe, Dr Carroll stated his belief that if matter were reduced to a sufficiently low temperature, the electron shells would 'shrink down within the proximity of the nucleus and exert tidal forces on it.' This would release the binding energy and cause a complete disruption of the nucleus. According to Dr Carroll, since heat was liberated during the formation of the nucleus (a light one, presumably), in its disruption the heat of formation would have to be taken up again, so that once a reaction had been started it would lead to a further absorption of heat and so to a self-sustaining reaction as long as raw material were supplied. The Dean could give no idea as to what temperature would be needed to initiate the reaction, but he mentioned that he did not consider −459·6°F to be the absolute zero of temperature.

As to the utilisation of the energy from the disrupted nucleus, Dr Carroll said that heat would not be the main form of energy. In this process the 'particle energies' would be the basic form, and the heat only 'secondary.' He had been mostly interested in rocket propulsion and, using this primary energy, he had found that there was really no limit to the speed that could be attained provided the rocket carried enough fuel to sustain the acceleration long enough.

During his work, Dr Carroll had found that practically all the results of the Einstein theory are erroneous. 'Even though they may agree with experimental facts they give the wrong interpretation of those facts—the variations of forms are assigned to the wrong quantity.' His modifications to the theory showed that the velocity of light is not the maximum attainable, nor is there any increase of mass with velocity. Consequently, there is no theoretical reason why a rocket should not exceed the speed of light. Asked on the radio programme about fuels for the reaction, he replied that a silicon compound such as sand would be suitable.

Curiously enough, the US authorities have decided not to place any security restrictions on this material and the Navy scientist hopes to start laboratory work within a year. Fortunately, no danger of an uncontrolled reaction is feared—Dr Carroll's calculations indicate this.

A new packaged reactor

A completely packaged 1000kW reactor for Dominica was announced last month from the Glenn L. Martin Company in Baltimore, Maryland. Of the pressurized water type, the reactor uses 5,000 elements of slightly enriched uranium. A feature of the design is that all the components are built inside eight aluminium pods which can be transported by air if necessary. On assembly, these pods remain as the permanent housing for the components. The total load is about 12 tons. According to Glenn Martin Nuclear Division chief, T. Nagey, the Dominican reactor will cost under $1m, not counting the generation plant. The same design could be built in capacities of 0·5 to 5MW. No further details are available at present, although photographs of what appears to be core assembly have been released. No delivery dates are quoted.

The BNEC Calder Hall Symposium

THIS ISSUE OF NUCLEAR POWER is unusual in that we are devoting almost the entire available space to the proceedings of the British Nuclear Energy Conference's Symposium on Calder Hall power station. This was held in London on November 22-23 and included 19 papers by those from the UKAEA and British industry who were most closely concerned with the project.

For the greater part, it is quite impossible to do more than print an abstract of each paper highlighting some point of interest. Nevertheless as far as the future is concerned, two contributions seem to us of outstanding importance—R. V. Moore's on *The development of gas-cooled reactors for power production* and *Basic Design of Reactor* by G. Packman and B. Cutts, and these have been included at some length. The first is important because it indicates very clearly how future British power stations will be built during the next decade or two: the second, because it deals with a subject of fundamental importance to the gas-cooled reactor—the core and fuel element parameters.

In studying the papers it must be recognised that although all the Calder experience will be of immense value in building our nuclear programme, many of the technical features used will probably not be employed again owing to the totally different design requirements and this has constantly been borne in mind in making the selections.

The complete proceedings of the symposium will be published in the BNEC Journal in April and July 1957.

LE PRÉSENT NUMÉRO du journal NUCLEAR POWER est consacré presque exclusivement à la discussion au sujet de la centrale nucléaire de Calder Hall, tenue au cours de la Conférence de l'Énergie Nucléaire en Grande-Bretagne (Londres, 22–23 novembre, 1956). La discussion embrasse 19 communications presentées par les membres du personnel de l'Énergie Atomique au Royaume-Uni ainsi que des firmes britanniques qui ont construit cette installation. Le numéro contient des résumés détaillés des communications plus importantes, et des résumés plus brefs d'autres communications. Le texte complet et la discussion seront publiés dans le journal de la Conférence aux mois d'avril et juillet de 1957.

DAS VORLIEGENDE HEFT der Zeitschrift NUCLEAR POWER ist fast ausschliesslich der Diskussion über die Kraftzentrale in Calder Hall gewidmet, die während der in London am 22/23. November 1956 stattgefundenen britischen Kernenergie-Konferenz gehalten wurde. Die Diskussion umfasste 19 Vorträge, die von den Mitgliedern der Atom energiebehörde Grossbritanniens sowie der britischen Firmen, die die Anlage gebaut hatten, vorgelesen wurden. Ausführliche Referate der wichtigeren Aufsätze und kürzere Zusammenfassungen anderer Aufsätze sind miteingeschlossen. Der volle Text sowie Diskussion werden in dem April- und Juli-Heft- der Konferenz-Zeitschrift veröffentlicht werden.

EST ENUMERO de NUCLEAR POWER está dedicado casi por completo a la reunión que sobre la central electroatómica de Calder Hall celebró la Conferencia Británica de Energía Nuclear en Londres el 22–23 de Noviembre de 1956. Durante la reunión se estudiaron 19 trabajos presentados por miembros del personal científico de la Comisión de Energía Atómica del Reino Unido y de las compañías británicas que construyeron la central. Incluimos extensos sumarios de los trabajos más importantes y cortos sumarios de los restantes. El texto completo y las discusiones serán publicados en la revista de la Conferencia en abril y julio de 1957.

НАСТОЯЩИЙ НОМЕР журнала NUCLEAR POWER посвящен почти исключительно беседе на тему электроцентрали Колдер Холл, проведенной во время великобританской Конференции по Ядерной Энергии, состоявшейся в Лондоне 22-23 ноября 1956 г. Предметом беседы было 19 статей, представленных сотрудниками Атомной Энергии в Соединенном Королевстве и великобританских фирм, которыми строился завод. Номер содержит обширные рефераты более важных статей и краткие резюме других статей. Полный текст и дискуссия будут опубликованы в журнале Конференции в апреле и июле 1957 г.

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19 MOORE on

Development of gas-cooled reactors for power production

IF THE CALDER PLANT were run as a power station, and no value were attributed to the residual plutonium, it would produce electricity at about a penny per unit. This would not be competitive with coal-fired stations in the United Kingdom and so in future plant this cost must be reduced.

As with conventional plants, the cost per unit may be taken as the sum of the capital charge, the fuel charge and the cost of operation and maintenance.

Let A = capital cost of the complete station, £

U = cost of uranium fuel elements per tonne, £

Q = heat rate of the reactor(s), MW

η = overall efficiency = $\dfrac{\text{electrical output}}{Q}$

L = load factor

m = average uranium fuel rating, MW/tonne

D = irradiation dosage of the fuel, MWD/tonne

= total heat energy released per tonne

Further, assume that interest and redemption on capital is charged at 4% per annum and that the plant has an economic life of 20 years.

Then:

(i) The capital charge

$$= \frac{2A}{Q\tau_i} \times \frac{1}{L} \times 10^{-6} \text{ d kWh (sent out)} \qquad (1)$$

(ii) Since Q/m tonnes of uranium is always locked up in the reactor(s), there is an associated interest charge on the capital involved.

Fuel inventory charge

$$= \frac{1{\cdot}1U}{m\tau_i} \times \frac{1}{L} \times 10^{-6} \text{ d kWh (sent out)} \qquad (2)$$

Here U is the cost of the uranium fuel elements delivered to the power station and is considered to include an overhead component for fuel in the 'pipeline.'

(iii) As the reactor operates, uranium is consumed.

Fuel consumption charge

$$= \frac{U}{D\tau_i} \times 10^{-2} \text{ d kWh (sent out)} \qquad (3)$$

This assumes that the uranium is passed once through the reactor; possibilities of recycling are considered later. No value is attributed to the residual plutonium.

The total cost per unit (s.o.) is the sum of eqns (1), (2) and (3) together with the unit charge for operation and maintenance.

Table I shows the composition of the cost per unit from the Calder Works if the plant were operated at 80% load factor as a nuclear power station and the fuel irradiated to an average value of 3000MWD/tonne, it being assumed that the fuel elements cost £20,000/tonne.

Table I *cost per unit*

cost component	cost	
	d	%
capital charge	0·56	53
fuel inventory charge	0·10	9
fuel consumption charge	0·35	33
operation and maintenance	0·05	5
total	1·06	100

In considering the effect of the variables in eqns (1)-(3) in reducing the cost per unit, these figures may be used to give a rough 'weighting' factor.

As with all power-producing plants, a high load factor leads to a reduction in the capital charge component of the cost per unit. With a nuclear plant of the type under consideration, an additional component—the fuel inventory charge—is similarly affected. These plants, passing through a phase of high capital cost, are therefore suitable as base-load units. This happens to accord in the United Kingdom appropriately with the necessity to generate as much power as possible from resources other than coal. To operate at a high load factor implies a high order of plant availability and no doubt the design of future nuclear power stations will incorporate improvements over the Calder Works in this respect, e.g. charging and discharging uranium while the plant is operating at power.

Other than L, the variables in eqns (1)-(3) may be arbitrarily classified into two categories. Firstly 'commercial factors', which are dependent on the market values of materials, equipment and labour: secondly 'design factors', which depend on design skill and the fundamental scientific and technical knowledge on which the design must be based.

Considering the capital charge, which constitutes about 50% of the unit cost (see Table I, the term $A/Q\eta$ in eqn (1) is the capital cost per MW (s.o.) for the plant. This contains both 'commercial' and 'design' factors. The cost of the station, the term 'A,' depends mostly on the cost of materials and labour but also to some extent on economical design. The denominator of the expression on the other hand is entirely a design factor, the capital charge decreasing as the electricity output increases for a given capital investment.

The fuel inventory charge constitutes a small percentage of the cost per unit (<10%) and is composed of a 'commercial' factor—the cost of uranium—and 'design' factors m and η.

The fuel consumption charge (about 35% of the unit charge for D=3000MWD/tonne) is dependent on the 'commercial' factor U and 'design' factors η and D. The only factor to which the whole unit cost is proportional (in the inverse ratio) is the overall efficiency η, and small improvements are therefore important. Fig. 1 shows the importance of being able to irradiate the fuel for as long as possible; particularly striking is the way in which the cost per unit falls rapidly up to about 2000MWD/tonne.

Stretching the burnup

The ability of a natural-uranium charge to achieve a long irradiation depends mainly on two factors; neutron balance, and the ability of the fuel elements to withstand the irradiation without an excessive number of failures. As the ^{235}U content of the charge is consumed, it is replaced to some extent by plutonium formed from ^{238}U by neutron capture, and a small fraction of the plutonium so formed is itself fissioned. Recent experimental results from the Calder plant tend to confirm that 3000MWD/tonne is obtainable before poisons accumulate in the fuel elements to the extent of inhibiting the chain reaction. The metallurgical limits on the life of the fuel elements arise from the tendency of uranium to increase in volume when irradiated at temperatures approaching the alpha/beta change point of 660°C. Knowledge of the extent of this increase is not at present complete but there is mounting evidence that 3000MWD/tonne is attainable. Indeed, it is likely that this limit and the operating temperature may be raised by the adoption of certain alloys of uranium stabilized in the gamma phase.

So far in this analysis, no value has been assigned to the plutonium formed in the irradiated fuel elements. Ultimately its value will depend on its worth as a fissionable material. Its *minimum* value will, of course, be its cost of production, i.e. the cost of irradiation in reactors and subsequent chemical separation on discharge.

Calder limitations

The performance of the Calder Plant was limited primarily by the plate thickness of the reactor pressure vessel, and the maximum temperature of the system.

The core diameter was chosen so that the plant would operate at full power using natural-uranium fuel, with a small excess reactivity for satisfactory control. With 2 in. plate for the pressure vessel, the operating pressure was 100 lb/in² gauge. The maximum temperature of the system was judged to be 400°C at the surface of the hottest fuel elements. The economic performance of this type of plant improves as these limits are raised.

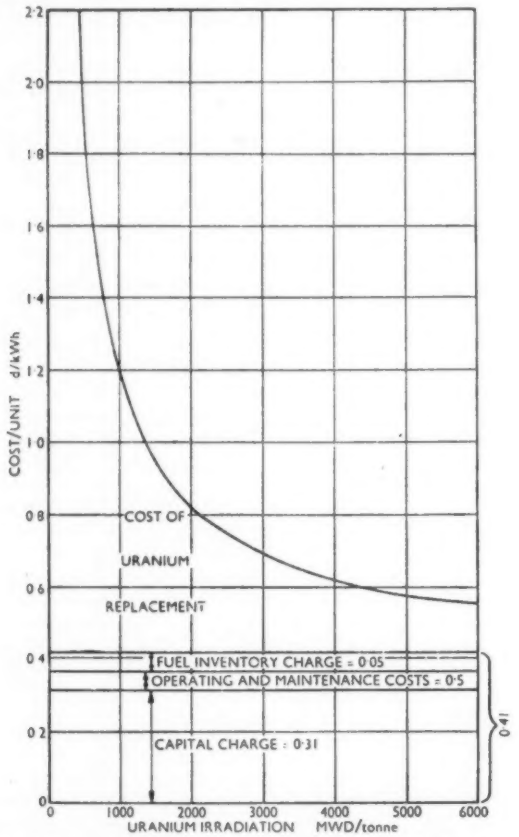

Fig 1 *cost per unit from a plant costing £125/kw(so) operating at 80% load factor, 25% efficiency on natural uranium costing £20,000/tonne*

Thicker pressure vessel shell

Visualize a graphite core, with the uranium channels located on a square lattice, surrounded by a graphite reflector 3 ft thick within a cylindrical pressure vessel, with 1-ft radial clearance between the inside of the pressure vessel and the graphite; it can be shown that

$$Q = \frac{0{\cdot}113(d_p - 8)^2 q\,\alpha}{p_s^2} \qquad (4)$$

where Q = heat rate of the reactor, MW

q = heat output of most highly rated uranium channel

d_p = internal diameter of pressure vessel, ft

p_s = pitch of uranium channels, in.

α = radial form factor of neutron flux, mean/maximum

The Calder core diameter is chosen so that the reactor is just supercritical at full power. Therefore a core of similar design and nuclear properties, whose diameter is greater will have excess reactivity above that required for operation. This can be profitably exploited by introducing absorbing material into the core in such a way that the neutron flux is flattened and the value of α raised. Thus increasing the pressure-vessel diameter, d_p produces marked increases in Q, not only because of the increased number of channels, but also because of increases in the value of α.

It is interesting to note from eqn (4) the importance of maximizing q. In practice this must be done in relation to ϕ, the ratio of pumping power to q, and the temperature rise ratio r. The effectiveness of the extended surfaces for heat transfer from the fuel elements to the coolant is important in this facet of reactor design. It can also be seen from eqn (4) that Q is increased as the lattice pitch p_s is decreased, but this has repercussions on the nuclear and mechanical design. Squeezing the lattice can only be exercised profitably over a limited range.

Before relating Q to the design of the reactor vessel, it is necessary to assess the effect of the absolute pressure of the circulating gas. Increasing gas pressure reduces the fraction of the reactor heat rate required for the gas circulation according to an inverse square law. Increasing the pressure therefore brings diminishing returns. The final selection of the best value must be related to the optimization of a specific design of plant. In considering limited extrapolations from the Calder design, however, it is sufficient to consider an increase of, say, 25-50%. Taking values of gas pressure in this range, and assuming a cylindrical pressure vessel, it is possible to evaluate eqn (4) to give values of Q following increases in reactor-vessel plate thickness (Fig. 2).

The marked effect of increasing the thickness of the pressure-vessel wall on the heat rate of the reactor can be clearly

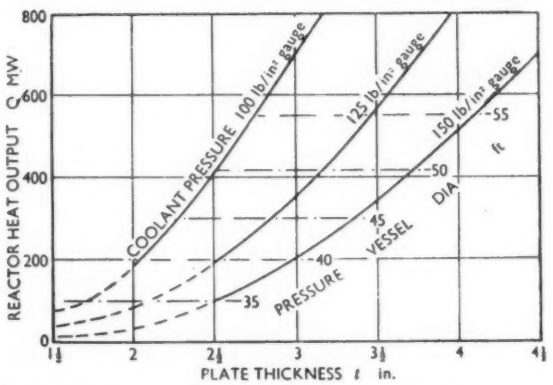

Fig 2 *for constant ratio of pumping power to output of highest rated channel, total output rises steeply with increasing plate thickness*

seen. For 3 in. thick plate, for example, the heat rate of the reactor could be 400-500MW. It is obvious that the capital cost of the plant would increase proportionately much less than this increase in heat rate and so the capital cost per kW could be expected to drop considerably from the figure for the Calder plant.

The above is a somewhat over-simplified approach to assessing the effect of increasing the size of the reactor. For example, there are several alternatives to a simple cylindrical pressure vessel fabricated in mild steel. But in general it can be concluded that increases in size, accompanied by limited increases in gas pressure, materially reduce the cost per kW, without the need for further scientific or technical developments. This has immediate importance as nuclear power stations can be built of improved performance whose reliability is underwritten by the operating experience of the Calder Works.

Putting up the maximum temperature

Increasing the maximum fuel-element temperature increases advantageously the values of Q, η and m (eqns (1), (2)). The question remains whether the effect of these improvements would be offset by unwanted changes of other factors, e.g. increases in U. The answer is involved.

For service in a reactor, the uranium is clad with a metal of low neutron cross-section, to prevent escape of the radioactive fission products into the closed primary coolant circuit and to prevent any chemical reaction between the uranium and coolant. The main possibilities are shown in Table II. Stainless steel (18/8/1) has been included, although its neutron cross-section is relatively much higher than the other possibilities.

Table II *possible uranium cladding materials*

	Al	Mg	Be	Nb	Zr	stainless steel (18/8/1)
neutron cross section, cm-1	0·0118	0·0023	0·00011	0·061	0·0076	0·227
melting point, °C	660	650	1284	2415	1850	1500
thermal conductivity, C.H.U./h ft deg C	130	90	70	36·4	14·4	9·2
density at 20° C	2·7	1·74	1·85	8·57	6·5	7·9

This table shows that it is not possible to raise the maximum temperature of fuel elements, clad in either magnesium or aluminium, much above the value of 400°C adopted for the Calder plant, owing to the low melting point of these cladding materials. Alternative materials Be, Nb, Zr and stainless steel have values of thermal conductivity considerably worse than either Al or Mg. This, coupled with the increased heat-flux associated with the desired higher rating of the fuel, means that the fin efficiency of any extended surfaces, from fuel elements clad with one of the higher melting-point metals, would fall to such a low value that the fins would cease to be effective.

The alternative is to increase the primary surface for heat transfer by spreading the uranium, but maximum reactivity is obtained with a fuel element shape, like a solid rod, which has a small surface to mass ratio. Raising the fuel temperature by a substantial margin from 400°C, therefore, implies a discontinuity of the present design. Not only must high-temperature fuel elements clad in little-known metals be developed, but a change in shape is involved which probably necessitates the use of enriched fuel.

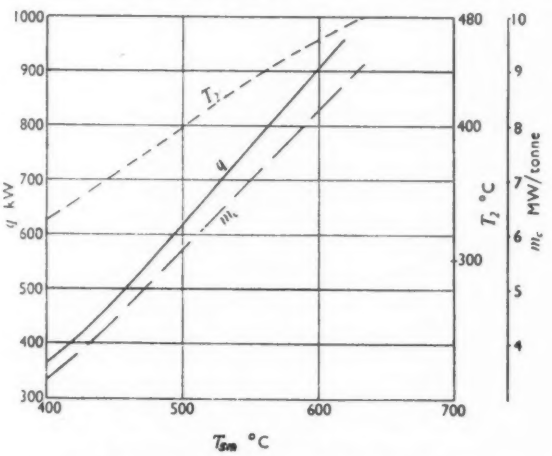

Fig 3 *with the surface/mass ratio of the elements increased threefold over the solid rod case, the channel heat rate q, the average rating of uranium in the highest-rated channel m_c and the channel gas outlet, temperature T_2, all increase rapidly if the maximum surface temperature of the elements (T_{sm}) is allowed to rise*

For a rough assessment of the effects, assume a uranium configuration increasing the surface-to-mass ratio by a factor of 3 over the solid rod case, and a channel 20 ft long through which CO_2 at a pressure of 150 lb-in^2 is pumped. Further, assume that the gas enters the channel at 200°C and that the ratio ϕ is 2%. Fig. 3 shows the effect.

The beneficial effects of increased fuel element temperature on the performance of the reactor are at once apparent. The rising values of channel gas outlet temperature from the reactor enable the overall efficiency of the plant to be raised. The channel gas outlet temperature is higher in the less highly rated channels of the reactor so that the mixed or bulk gas outlet temperature is somewhat higher than the values of T_2 plotted in Fig. 3. Making some assumptions which are typical of this type of plant, Fig. 4 shows the variation of overall efficiency against the bulk gas outlet temperature T.

For plants first using high-temperature fuel elements, the question arises how far the maximum fuel-element temperature can be raised. This is a critical question for the designer

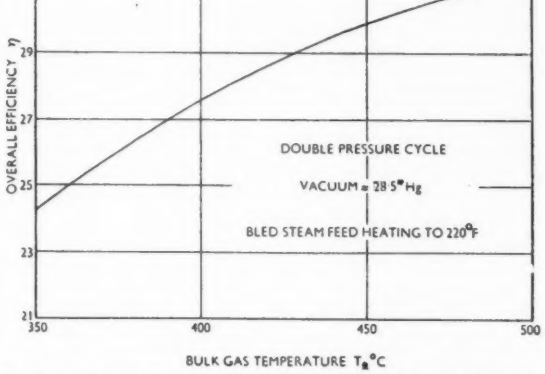

Fig 4 *with a double pressure steam cycle using feed heating, increasing gas temperatures give improved efficiency*

to answer, being a compromise between the best possible performance and the required degree of reliability in operation. In finality, the limits can be established satisfactorily only from experience of running plants.

Using data from Figs. 3 and 4 and evaluating eqn (4) with appropriate value of p_s, Table III compares an extrapolated Calder design, having a reacting core 40 ft in diameter, with a plant of the same size core but having a maximum fuel-element surface temperature of 600°C, a value little better than a guess.

Table III *comparison of extrapolated Calder design (case A) and with maximum fuel-element surface temperature of 600°C (case B)*

	Q MW	η_1 %	m MW/tonne	Q_E MW
case A: larger Calder design	400	25	2	100
case B: high-temp. reactor				
(i) flattened	1400	31	5·8	433
(ii) unflattened	1100	31	4·5	340

The increase in output and rating would substantially reduce the capital cost per kW of the plant, but as explained

above the uranium would probably require enrichment, which would increase the fuel cost. In this respect the possibility of recycling plutonium is relevant; this is discussed later.

The heat rates from the reactors in cases B (i) and (ii) are rather large from a single unit and in a specific design it might be beneficial in optimization, to decrease the core diameter, raise the gas pressure of the system and use larger temperature differences in the heat exchangers. This would reduce the size and cost of the external CO_2 circuit, including the heat exchangers, and produce a more balanced design, which would be reflected in a favourable cost per kW for the plant, even if the net output was reduced.

The development of gas-cooled reactors has been focused in the United Kingdom so far on the base-load application. The substantial increase in fuel rating m obtained by high-temperature operation increases the economic feasibility of plants of lower power output and for lower load factor, using slightly enriched fuel.

The difficulties associated with the development of a high-temperature plant should not be underestimated. The basic compatibility problems are again thrown into sharp relief. CO_2-uranium, CO_2-graphite, CO_2-steel, CO_2-canning-material reactions all enter a more active phase. The successful development of fuel elements (using a cladding metal on which experience is limited) to withstand the damage of long irradiation at high temperature requires extended application of very substantial resources.

Fuel economy

By 1963/64 onwards, by-product plutonium should be available in substantial quantities. The cost of this when separated from irradiated fuel, will probably be less than that of enriched uranium.

How may by-product plutonium most profitably be used, once supplies have been established? There appear to be at least four important possibilities:

(i) In new thermal reactors requiring initial enrichment, e.g. high-temperature gas-cooled reactors.

(ii) In fast-neutron, breeder reactors operating on a Pu-^{238}U cycle and producing power. This leads to balanced fast and thermal reactor schemes in which a comparatively large fraction of the ^{238}U is used, arising from the fact that fast reactors breed more fissionable material than they consume.[3]

(iii) In fast or thermal reactors as the fissionable material for a Pu-Th 'transition cycle' producing power and ^{233}U as a by-product. The ^{233}U might subsequently be used in a self-sustaining ^{233}U-thorium cycle in thermal reactors, if these prove practicable, or might be used as the fissionable material in fast reactors, breeding from ^{238}U or thorium.

(iv) In power plants requiring highly enriched fuel, e.g. plants designed with a large power/weight ratio.

As this paper is considering developments in gas-cooled reactors, possibility (i) above is examined in more detail.

Using plutonium

In a thermal reactor fuelled with uranium, ^{235}U is fissioned and some of the ^{238}U is converted by neutron capture into ^{239}Pu, which is fissionable by thermal neutrons. By neutron capture, higher isotopes of plutonium are also formed and constitute an important fraction of the plutonium. On a 'once through' system in which the charge is irradiated up to, say, 3000MWD/tonne, a small proportion only of the plutonium is burnt and the discharged fuel elements contain plutonium, depleted uranium and fission products. In chemical separation plants, similar to the full-scale plants which the UKAEA have now been operating for some years, the constituent parts can be separated. The possibility therefore arises of returning the plutonium and part of the depleted uranium to the fuel element fabrication factory, there to be reconstituted with new feed uranium into fuel elements for charging into the reactor. Fig. 5 illustrates this fuel cycle.

If the plutonium is recycled, eventually an equilibrium condition is reached in which the rate of burning plutonium is balanced by the rate of production of fresh plutonium. This is possible in a reactor with a conversion factor of less than unity, if the fissionable material, short of the amount required for the reactor to operate, is made up from ^{235}U in new uranium fed into the system. The analysis of such a system is complicated by the fact that as the plutonium is taken to longer irradiations the higher isotopes influence to an increasing degree the performance of the reactor. By successive neutron capture ^{239}Pu can become ^{241}Pu, ^{242}Pu and ^{243}Pu. ^{243}Pu is radioactive with a short half-life (5 h) and effectively decays almost immediately on formation to ^{243}Am, which would be removed in chemical processing after irradiation, ^{240}Pu, ^{241}Pu and ^{242}Pu build-up during the approach to the equilibrium system, when the rate of their formation is equal to their rate of destruction by natural decay or neutron capture. ^{240}Pu and ^{242}Pu are *not* fissionable isotopes, but ^{241}Pu is.

The effect of the higher isotopes of plutonium can be seen from Table IV, the values being typical of a reactor of the type shown in Case B of Table III. The mean moderator is assumed to be 700°K. The table shows the number of Pu atoms required to replace one ^{235}U atom without altering the reactivity. The adverse effect of ^{242}Pu in the system is clearly demonstrated by these figures.

Table IV *number of Pu atoms required to replace one ^{235}U atom without altering the reactivity*

	number of Pu atoms
for pure ^{239}Pu fuel	0·44
for 3000 MWD/tonne Pu from a natural U reactor	0·75
for equilibrium plutonium	2·38
for equilibrium plutonium without ^{241}Pu	0·99

There are a number of variations of the basic cycle [4,5]; in this paper some of the simpler relationships are defined and a numerical example is quoted for explanatory purposes. From Fig 5 it can be seen that

$$E_F = E_M(1-R) + RE_R \tag{5}$$

An important case occurs when $E_F < 1$ for in this case natural uranium make up can be used, i.e. $E_u = 1$.

Now let

$$w = \frac{\text{mean concentration of } ^{235}\text{U in reactor}}{\text{initial concentration of } ^{235}\text{U in reactor}} = \frac{\bar{E}}{E_F} \tag{6}$$

ϕ = thermal neutron flux

σ_{235} = total absorption cross-section of ^{235}U

T = fuel irradiation time

Then

$$w = \frac{\int_0^T e^{-\sigma_{235}\phi_t} dt}{T} = \frac{1-e^{-\sigma_{235}\phi T}}{\sigma_{235}\phi T} = \frac{1-h}{-\log_e h} = \frac{\bar{E}}{E_F} \tag{7}$$

where $1-h$ = fraction of ^{235}U destroyed per cycle.

The equilibrium enrichment E depends only on the reactor design and the nuclear constants and is independent on the actual recycling procedure. For a given reactor, $\bar{E}$ can be calculated, therefore (7) gives the relation between burn-up per cycle and the fraction of ^{235}U supplied from the feed material.

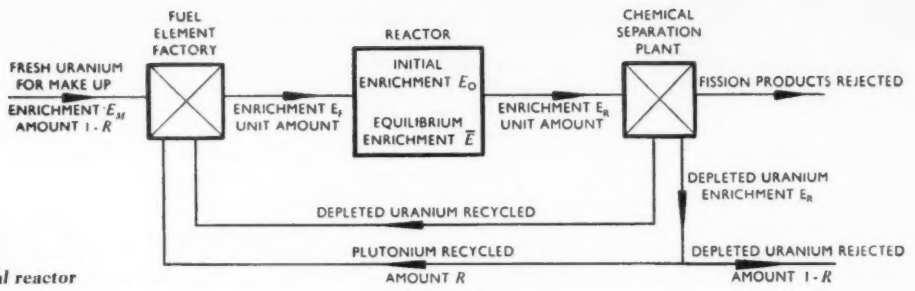

Fig 5 *how plutonium may be recycled through a thermal reactor*

Having defined (1—h), it is apparent that

$$E_R = hE_f \qquad (8)$$

Eqn (8) gives the relation between concentration of reject uranium and the concentration of the feed uranium for a given burn-up of ^{235}U per cycle. Lastly combining (5), (6) and (8), we may write

$$R = \frac{E_M - \frac{\overline{E}}{w}}{E_M - hE_F} \qquad (9)$$

or if $E_M = 1$,

$$R = \frac{1 - \frac{\overline{E}}{w}}{1 - hE_F} \qquad (10)$$

Eqn (10) gives the fraction of depleted uranium recycled for a reactor of given design in terms of burn-up per cycle and the ^{235}U content of the uranium feed, the make-up being natural uranium.

The effect of fuel recycling may be illustrated by specific example. Consider the reactor associated with case B (ii), Table III, operating on an equilibrium cycle, each successive charge being irradiated to 3000MWD/tonne. For this case:

Initial enrichment = 1·16; $\overline{E} = 0{\cdot}63$; $E_F = 0{\cdot}71$; $R = 0{\cdot}65$; $E_R = 0{\cdot}56$ from which $(1-R) = 0{\cdot}35$ and therefore each tonne of natural uranium make-up would produce 8500MWD of heat, or the utilization of uranium fuel resources would be improved over the once through system by a factor of 3. The reactor design chosen in this example is not particularly well adapted to operate on fuel recycling and this factor might conceivably be increased, by a design more appropriate for this system of fuelling. It is clear that potentially the important advantages of fuel recycling are:

(i) It could reduce the natural uranium requirement to meet a given power demand by a significant factor

(ii) Under certain conditions, applicable to gas-cooled graphite-moderated reactors, designs requiring initially a charge of slightly enriched uranium, can be subsequently fed with natural uranium once equilibrium conditions are reached.

An economic assessment of fuel recycling at the present time cannot be made with any exactness. The effect of hold-up of fuel in processing, the relative quantities in the reactor and 'pipeline,' and the effect of processing-rate/feed-rate are some of the factors involved. The cost of fabricating fuel elements with α-active plutonium is another important factor in determining the overall economy of fuel recycling. Note that if all the plutonium is recycled in the reactor in which it is produced, the net electricity cost does not depend, in the equilibrium state, on fixing a value of plutonium. In fact, a lower limit for the value of plutonium can be deduced from considering such a cycle, since it would be uneconomic to sell plutonium at such a low price that the net cost of electricity from the reactor which would use recycled Pu instead of ^{235}U make-up, is greater than if the plutonium were recycled.[5]

Changing the gas

For reactors so far discussed it has been assumed that the coolant gas is CO_2. In addition the following might be considered: hydrogen, helium and nitrogen.

Coolants must be compared on a number of criteria—safety, cost, availability, purity, thermal and irradiation stability, chemical compatibility, neutron absorbing properties, the degree to which they become radioactive—all in addition to their heat transfer properties. It is scarcely surprising that an ideal coolant does not exist.

In comparing heat transfer properties of gases, reference must be made to the type of heat-transfer surface. Two cases have been discussed in this paper:

(i) Where reliance is placed on primary heat transfer surface

(ii) Where most of the heat is transferred from extended surfaces.

Case (i) is analysed by Diamond and Hall[6] under certain specified conditions and assuming Reynolds' analogy to apply. A criterion ($M^2.c_p^3$) is developed for comparing gases used to remove the same amounts of heat from channels of the same length and area under the same temperature and pressure conditions. The ratio of heat removed to pumping power is proportional to $M^2.c_p^3$. Values at 300°C for the four gases under consideration are shown in Table V.

Table V *values of* $M^2.c_p^3$

gas	$M^2 . c_p^3$
nitrogen (or air)	13·0
helium	30·6
carbon dioxide	31·4
hydrogen	167·0

M = molecula. weight; c_p = specific heat

The ratio of pumping power to heat output for a given gas is proportional to the square of the heat output, so that by substituting, for example, hydrogen for carbon dioxide, an increase in heat output by a factor of $\sqrt{167/30{\cdot}65}$, i.e. of 2·33, could apparently be obtained. However, with unchanged inlet and maximum fuel element temperatures a drop in gas outlet temperature would occur. Diamond and Hall point out also that the criterion is not completely satisfactory, because the heat-transfer area is a variable dependent on the gas properties, and unacceptable area might be needed to obtain a given performance.

The same criterion applies also to transverse fins of the type used in the Calder Plant, for which Reynolds' analogy does *not* apply, but for which a fin efficiency correlation can be made (Fortescue and Hall, this symposium). Similar criteria could no doubt be developed for other types of extended surface. If a 'better' gas is substituted for the original one, and an attempt made to restore the ratio of pumping power to heat output, the outlet temperature from the reactor can be expected to fall seriously in all cases of extended surface, owing to the reduced efficiency of the extended surface.

The only satisfactory way of comparing the performance of different gases is to evaluate for a specific design. In general,

when this is done the differences are not so marked as expressions like ($M^2.c_p^2$) suggest. CO_2 was the gas chosen for the Calder Hall reactors because it was the best compromise between all the requirements. As the temperature of reactor systems is raised, new conditions will be created and helium or nitrogen may supplant CO_2, as, comparatively, they are inert gases. Hydrogen is inert at ordinary temperatures but is chemically active at elevated temperature; it is also highly inflammable. Considerable research work would have to be carried out before its feasibility was established for cooling nuclear power reactors; however, its superior heat transfer properties and favourable nuclear properties are a considerable incentive.

Ceramic fuels

As the fuel element temperature is raised, interest is stimulated in ceramic fuels, i.e. compounds of uranium, plutonium and thorium with oxygen and carbon. The properties of uranium, uranium carbide and uranium oxide are compared in Table VI.

Table VI *properties of uranium, uranium carbide and uranium oxide*

	U	UC	UO_2	UC_2
melting point, °C	1133	2250	2500	2260
density	19	13·5	11	11·28
thermal conductivity at 50° C, C.H.U./h ft deg C	3·75	4·6	0·29	0·47

Compared with the metals, they have much higher melting points, are brittle, and soften only at comparatively high temperatures. Most ceramics have a thermal conductivity much lower than metals but this is not the case with the uranium carbides, which have similar values to the uranium metal.

Uranium oxide was used in the first reactor built in the United Kingdom (GLEEP) but uranium metal was later preferred as its density is higher, a favourable property from the nuclear point of view, particularly important when natural uranium is used. As concentrated fissionable materials become available, however, interest in the ceramic forms of uranium will probably return. Generally speaking, ceramics are more resistant to coolant attack than metals, UO_2 is inert both to CO_2 and hydrogen. UO_2 and UC are reasonably stable in air although UC_2 and ThC_2 are very reactive. In addition to their favourable high temperature properties, there is some experimental evidence to indicate that their irradiation resistance is considerably better than the metal.

VHT reactors

Ceramic fuels and the fact that graphite itself is a refractory material have led to the possibility of a very-high-temperature, gas-cooled reactor in which all metals are excluded from the core. This type of reactor has been given considerable impetus recently by Fortescue of Harwell. As a type it might be developed to meet the requirements of groups (iii) or (iv) of the section on 'Fuel economy.'

Fuel rating is generally discussed in terms of heat removed from a given mass of uranium (MW/tonne), a small proportion only of which, in natural or slightly enriched uranium, is fissile material. This definition of rating carries with it a concept of the size of the plant; possibly some 20% of the capital cost of a plant is inversely proportional to this figure. The fuel inventory charge (see eqn (2)) is also reduced as the rating is increased. Another way of expressing fuel rating is in terms of *fissionable material*, a concept more important in relation to fuel cycles. With natural uranium the fissionable material rating is 140 times the uranium rating. Table VII shows the uranium and fissionable-material ratings for the reactors discussed.

Table VII *uranium and fissionable-material ratings*

	uranium rating, MW/tonne	fissile-material rating, MW/kg
Calder Works	1·4	0·2
case A of Table III	2·0	0·3
case B (i) of Table III	5·8	0·8
possible V.H.T. reactor	—	1–2

With the VHT reactor the possibility exists of virtually 'diluting' the fissionable material with the moderator, in this case high, fissionable-material ratings are possible (see Table VII) and at the same time good neutron economy preserved.

At the high temperatures associated with this type of reactor (typically, a gas outlet temperature of 800°C (1472°F)) the problems associated with materials are acute. Attaining a high degree of thermal and irradiation stability of the graphite and the ceramic fuel at high temperature and high neutron flux presents a formidable research problem. So does preventing the spread of fission products into the primary cooling circuit. These ideally should be confined to the fuel, as with conventional fuel elements, clad in metal. The incentive for development, however, is high. It is calculated that the overall efficiency of such plants could exceed 40%, while the high fuel rating would lead to a further reduction in the capital cost per kW, when compared with high temperature reactors with metallic cladding of the fuel elements, as typified in Case B (i) of Table III.

Chance for gas turbine

The prospect of higher gas temperatures leads inevitably to the consideration of gas-turbine cycles. For plants of large power output, a cycle of the same general type as developed by Escher-Wyss is applicable. Stenning and Howieson of Chalk River, Canada, have carried out preliminary calculations for this type of plant, the general layout of which is shown in Fig. 6.

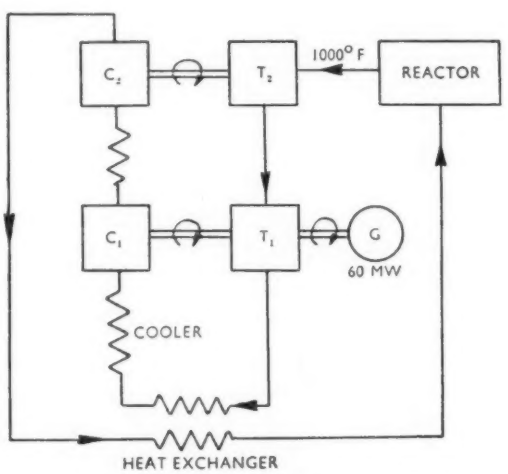

Fig 6 *in a proposed VHT reactor/gas turbine system, the h.p. machine drives the second stage compressor: the l.p. the 1st stage and the alternator*

Comparing the merits of CO_2 and helium, Stenning and Howieson conclude that the rotating machinery for the CO_2 cycle has approximately half the volume of that required for the He plant, but the heat exchangers have nearly double the volume, which suggests that marginally the CO_2 plant might be cheaper to build. In carrying out preliminary design

calculations for a 60 MW (electrical) plant they assumed a gas pressure of 300 lb/in² abs. and a top gas temperature of 538°C. These conditions are particularly interesting as they probably represent something near the minimum conditions for such a cycle, the machinery being large and costly yet possible to design and construct. Even at 538°C the calculated efficiency is 29% and if this temperature was raised to 677°C this would go up to 38%. For the capital cost of the plant to be competitive with steam plants it would appear, however, that the system pressure would have to be considerably higher than 300 lb/in² gauge.

Potentially the gas-turbine cycle becomes worth while in conjunction with the VHT type of reactor, but for the system shown in Fig. 6 to be feasible, fission products would have to be contained within the reactor.

Acknowledgments

The author wishes to acknowledge the help of Mr W. Bonsall and Mr J. Waters with the calculations for this paper, and Mr L. M. Wyatt for data on materials.

References

1 **A Programme of Nuclear Power** Cmd 9389, 1956, Feb (London: HM Stationery Office)

2 R. V. Moore, R. J. Haslam, G. Duffett and G. Packman: **A 200MW nuclear power station** AERE Report, 1954, Aug, No. UK/C

3 C. A. Rennie: **Economic power from fast breeder reactors** *J. Nucl. Energy*, 1954, 1, p 39

4 J. V. Dunworth: **Fuel cycles and types of reactor** *Proc. Int. Conf. Peaceful Uses Atomic Energy* (Geneva, 1955), Paper No. P/403, 1956, 3, p 14

5 P. W. Mummery and J. J. Syrett: **Fuel re-cycling in equilibrium uranium-plutonium thermal reactors** AERE Report, No. R/P 1915

6 J. Diamond and W. B. Hall: **Heat removal from nuclear-power reactors** *J. Brit. Nucl. Energy Conf.*, 1956, 1, p 227; also **Symposium on Nuclear Energy**, 1956, p 40 (London: Instn Mech Engrs)

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7 PACKMAN and CUTTS on

Basic design of reactor

FROM THE DESIGN STUDY for the Calder Hall reactor four important factors influencing basic design emerged:

(i) Magnesium had been discovered to capture neutrons to a smaller extent than had at one time been thought. This meant that the fuel elements could be contained in a sheath which, though substantial, would nonetheless absorb relatively fewer neutrons than the thin aluminium cans of previous fuel elements.

(ii) The quality of the reactor-type graphite had been improved so much that its absorbing power had dropped nearly 20% below that of the Windscale reactors.

(iii) In air-cooled reactors valuable reactivity is lost by the absorption of neutrons in nitrogen. The decision to use carbon dioxide as coolant made this reactivity available for other purposes.

(iv) The diffusion plant had come into operation. This meant that if necessary a small amount of enriched uranium could be used to improve the reactor charge should the reactivity of the reactor as built be too low for operational requirements. The achievement of a natural-uranium reactor was, however, regarded as of the utmost importance. If this flexibility had not been available the core diameter of the reactor might have had to be about 4 or 5 ft larger to ensure enough reactivity in hand to guarantee the operation of the reactor under design conditions.

These made is possible to specify a core, with 1 in. dia. rods on an 8 in. lattice, of active size 21 ft long × 31 ft dia. This was much smaller than had been previously thought possible at the desired rating and temperature.

The maximum thickness of plate for the pressure-vessel shell which it was considered could be successfully welded on site was 2 in. The core diameter and side-reflector thickness gave a pressure vessel diameter of 37 ft. These two considerations led to an operating pressure of 100 lb/in² gauge. It had been found that for given pumping power, circumferential fins on the fuel element gave better heat transfer than the longitudinal ones then in use. The resulting higher coolant temperature at outlet from the reactor meant better steam conditions and higher thermal efficiency.

When the design study was completed it was decided to build two reactors at Calder Hall on the lines indicated by the study and the work was transferred to Risley. The emphasis was shifted from electric power to plutonium production and it was therefore necessary to make a new survey of lattice parameters, the pressure-vessel size remaining fixed so that construction could proceed in parallel with the detail design of the core. The rest of this paper recounts the work of the 3 years from March 1953, which to a certain extent is still continuing. From time to time during these 3 years improvements were made both in the basic data used and in the methods of calculation. Furthermore, changes were made in the proposed scheme for loading the reactor with natural or enriched fuel, if use of the latter in fact proved necessary.

The nuclear calculations are so lengthy that it has not been possible to detail them, but attention has been concentrated on the line of development of the work. The flow calculations, which are shorter, have been described in some detail.

List of symbols

A flow area, ft²

c_p constant-pressure specific heat of coolant, C.H.U./lb °C

d_c channel diameter, ft

d_e equivalent diameter $= d_c - d_f$, ft

d_f fin tip diameter, ft

G coolant mass velocity $= W/A$, lb/ft² sec

k thermal conductivity of coolant, C.H.U./ft sec °C

k_m thermal conductivity of can, C.H.U./ft sec °C

L length of continuous uranium in channel, ft

L' extrapolated length associated with L, ft

r temperature rise ratio $= \dfrac{\theta_2 - \theta_1}{\theta_{sm} - \theta_1}$

r^* temperature rise ratio $= \dfrac{\theta^* - \theta_1}{\theta_{sm} - \theta_1}$

Re Reynolds number $= \dfrac{Gd_e}{\mu} = \dfrac{4W}{\pi(d_c + d_f)\mu}$

s hypothetical perimeter of can $= \pi d_f$, ft

St Stanton number $= \dfrac{h}{Gc_p} = \dfrac{hA}{Wc_p}$

W coolant mass flow, lb/sec

θ_1 coolant temperature at beginning of fuel elements, °C

θ_2 coolant temperature at end of fuel elements, °C

θ^* coolant temperature at point where the can-surface temperature is maximum, °C

θ_{sm} maximum can-surface temperature, °C

η_i ratio of heat produced in uranium to that produced in uranium and associated graphite

π circum/dia. ratio

μ absolute viscosity of coolant, lb/ft sec

Part I–NUCLEAR CALCULATIONS

The model used for reactor calculations

From a reactor-physics viewpoint a Calder Hall reactor consists of a cylindrical block of graphite containing a large number

of cylindrical uranium rods spaced on a square lattice. Each rod is clad in a magnesium sheath and is concentrically disposed in a coolant channel, the axes of the channels being parallel with the cylindrical axis of the graphite block. The whole of this graphite block is surrounded by a graphite reflector, 2–3 ft thick, the end reflectors being pierced by holes which are a continuation of the coolant channels.

The channels containing the fuel elements are, for the convenience of loading and unloading through the pressure vessel, arranged in square groups of 16. At the centre of each square is an additional channel through the graphite block into which a control rod can be inserted. Account is taken of the presence of this channel by a reduction in the apparent density of the graphite, the streaming of neutrons along the channel being neglected.

In making the latttice calculations the uranium rod must be assumed to be continuous along the channel, though in practice the channel contains several short uranium rods with the spaces between them filled by supporting structure. To simplify the calculations, the uranium is assumed to be continuous, though of reduced density, and the neutron-absorbing power of the intermediate supporting structure is added to that of the main body of the magnesium sheath and distributed uniformly over the length of the uranium.

The experimental results obtained from the start-up programme indicate that some of these minor design features may have been rather too conservatively accounted for in the theoretical work, and this is now being critically reviewed.

For practical purposes the work on nuclear calculations can be divided into three stages, although there is no real separation of one stage from another. The three stages are described in the following three sections.

Preliminary surveys

The original PIPPA design study at Harwell had been aimed primarily at the production of electrical power, but when the decision to build the Calder reactors was taken the emphasis was shifted to plutonium production and the design had to be revised to achieve that aim in an economical manner, to examine the possibilities, a new survey of lattice-pitch and rod-diameter combinations was undertaken. It was realized that if the reactor fuel were restricted to natural uranium it might not be possible to build within the limits of the pressure vessel a core giving the required output, e.g. a deficiency of $\frac{1}{2}\%$ in reactivity would mean a reduction of heat output of about 40% to establish a new reactivity balance.

For this survey the core diameter was fixed at 30 ft and for each lattice-pitch and rod-diameter combination the fuel enrichment was calculated that would make the reactor work at the highest possible power. In all cases the length of uranium was fixed at 20 ft. The maximcm amount of heat that could be taken out of a single fuel channel with the new circumferentially finned cans was by no means certain, so that the survey also included a small range of maximum channel ratings of from 160-200kW/channel. The results of this survey for the highest channel heat output are shown in Fig. 1. It was clear that the fuel element had to be of about 1·1 in. dia., and the lattice pitch not less than $7\frac{1}{2}$ in. to avoid a heavy bill for enriched fuel. Further conclusions could not be drawn from these results, however, since the basic information used was known to be rather pessimistic.

A more detailed survey was then made covering a restricted range of lattice-pitch and rod-diameter combinations and in addition to a fixed core-diameter of 30 ft, the total heat output of the reactor was also decided. The more important results are shown in Fig. 2. Improved data were used so that the enrichment figures in Fig. 2 are far less pessimistic than those in Fig. 1. In the nuclear data, uncertainties of course remained that might raise or lower the calculated enrichments by about 1% of the naturally occurring value, and the final selection of an 8-in. lattice pitch together with a 1·15-in.-dia.

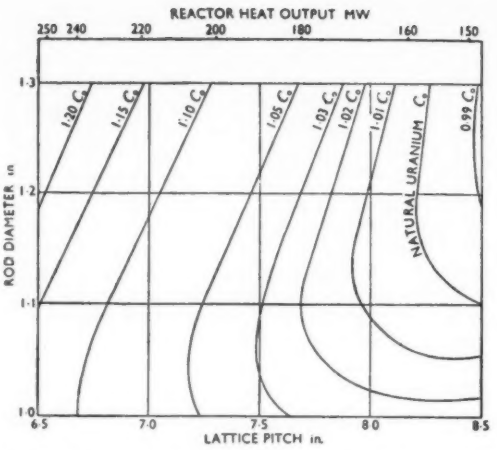

Fig 1 *lines of constant enrichment on plot of rod diameter against lattice pitch*

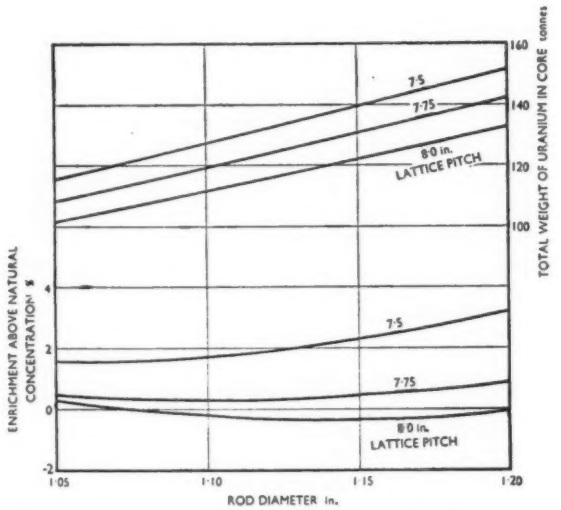

Fig 2 *enrichment and weight of fuel against rod diameter for three different lattice pitches*

fuel element gave the best possible chance of a reactor fuelled with natural uranium operating under design conditions.

Calculations for the Calder reactors as designed

When the preliminary surveys were made in 1953 many of the minor details of the reactor core were not yet decided. Such data as the spacing between individual uranium cartridges, the channel diameters, the actual quality of the graphite that would be available and the amount of uranium canning material that would be required were all yet to be determined by the design engineers. The survey calculations were therefore made using rough allowances for all these quantities and assuming that the reactor core would be uniform throughout. By early 1954, however, all the important data affecting the nuclear calculations had been fixed so that a new set of calculations could be made to assess the nuclear parameters of the reactor as it would be built and to determine the enrichment, if any, required for operation. At this time the reactor fuel charge was envisaged as being in two parts, a central cylindrical portion of natural-uranium fuel elements surrounded by an outer region of slightly enriched uranium, the proportions of each kind of fuel being determined by the enrichment that was convenient for use and the

actual reactivity developed by the lattice. The possible error in the lattice constants calculated from the data derived from exponential experiments had been assessed as equivalent to $\pm\frac{1}{2}\%$ in reactivity, and a convenient method of allowing for this would be by adjustment of the relative proportions of natural- and enriched-uranium fuels loaded into the reactor at start-up.

The reactor design data used for the nuclear calculations are as follows:

Reactor core

Fissionable material	natural uranium
Total weight of fissionable material, tonnes	130
Number of fuel element channels	1696
Diameter of fuel element channels	256 at 4·16 in. dia 576 at 3·95 in. dia 864 at 3·61 in. dia
Pitch of channels, in.	8
Number of control rod channels	112
Diameter of control rod channels, in.	3·25
Nominal core height, ft	21
Nominal core diameter, ft	31
Height of graphite, ft	27
Diameter of graphite (across corners), ft	36
Machined weight of graphite tons	1146
Core graphite density g/cm³	1·73
Core graphite absorption cross-section (measured in air in GLEEP), millibarns	4·0
Reflector graphite density, g/cm³	1·60
Reflector graphite absorption cross-section (measured in air in GLEEP), millibarns	4·8
Uranium rod diameter, in.	1·15
Length of uranium in channel, ft	20
Density of uranium, g/cm³	18·7
Absorption cross-section of cans and supports, cm²/ft uranium	0·51

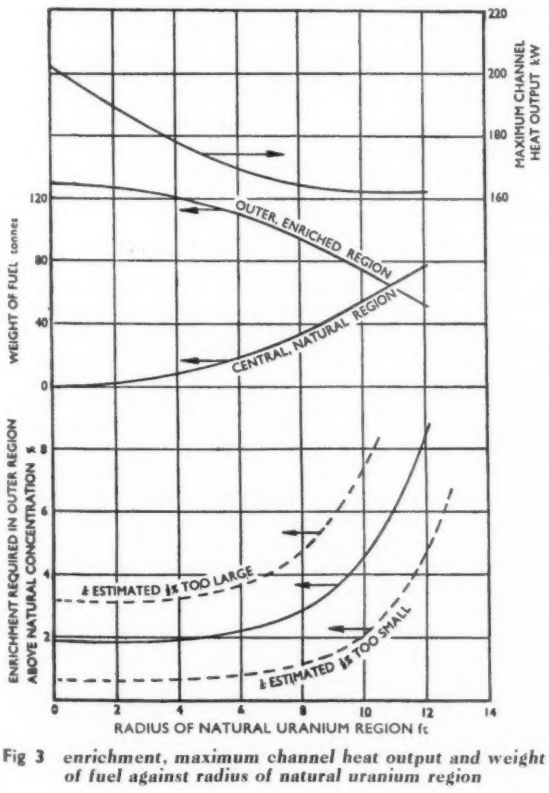

Fig 3 *enrichment, maximum channel heat output and weight of fuel against radius of natural uranium region*

The graphite structure is not uniform, there being variations in channel diameter, and to represent the reactor core a model was chosen with three zones of different channel sizes, the zones being concentric cylinders having axial uniformity.

Fig. 3 shows some of the interesting results. On this graph can be seen the effect of the uncertainty in reactivity inherent in the calculations. For example, if a 5% enriched-uranium fuel were chosen for the outer region the quantity required could be anywhere between 50 and 94 tonnes, a very wide variation indeed.

Final revision of calculations

By the middle of 1955 a large number of exponential experiments for graphite-moderated reactors had been completed at Harwell, and from the results a revision of the data used in lattice calculations was made. The effect of the revision was to increase the estimated reactivity of the Calder-type lattice by about 0·7%, although the possible uncertainty still remained at $\pm 0{\cdot}5\%$. This meant that the fuel charge instead of including a large proportion of enriched-uranium fuel elements, would be almost entirely natural uranium. Furthermore, there was a distinct possibility that the reactor would have some excess reactivity with natural uranium fuel only, so that the reactivity might have to be slightly reduced by adding absorbers and/or removing fuel.

The nuclear calculations were therefore revised once more using the new data, and the new lattice constants for the zones of the reactor core are given in Table I. Since the reactor could now be expected to operate with a charge of natural uranium, these lattice constants were statistically weighted to give the representative parameters of the equivalent uniform reactor. Recent experience during the start-up experiments has indicated that the use of the so-called 'statistical weights theorem' in this way is not satisfactory and that a proper analysis of the three-region core using two-group neutron theory should be used. To 'trim' the reactor and allow for the uncertainties in reactivity some steel absorber bars and some enriched-uranium fuel elements were provided along with the initial charge of natural-uranium fuel. The enriched uranium was rather more highly enriched than before since it was no longer convenient to produce the lower enrichments in small quantities, but care would have been needed in selecting the channels into which the enriched fuel would be inserted, for its high heat output could cause difficulties. The effect of the steel rods is shown in Table II.

Part II—COOLANT FLOW CALCULATIONS

In these calculations the unit is the individual fuel-element channel. The critical parameters are the coolant inlet and outlet temperatures, the limiting fuel-element temperature, the heat removed, and the power to pump the coolant through the channel. The pressure drop depends on the temperatures, so they must be found first. From a set of such calculations it is possible to choose a range of channel heat outputs for which nuclear calculations can be made. These in turn give heat-output distributions across the core, and hence the reactor heat output, total coolant mass flow, and bulk outlet temperature.

It is implied above that only one cycle of calculations is needed. In fact several cycles are completed before a firm design is reached.

Single channel

Given:

(1) Experimental heat-transfer and pressure-drop data for a certain geometry (Fortescue and Hall, this symposium)
(2) Coolant gas, inlet pressure and temperature
(3) Limitation on fuel-element temperature (throughout the design this has been taken as maximum can-surface temperature)

Heat transfer from can to coolant

Assumptions:

(i) Constant coolant mass flow
(ii) Constant coolant specific heat — along channel
(iii) Constant heat-transfer coefficient

(iv) Heat input of cosine form, symmetrical about the channel mid-point, and of base length equal to the length of the uranium plus two extrapolation lengths, but zero beyond the ends of the uranium

(v) Ratio of heat input from uranium alone to that from uranium and graphite constant along the channel

(vi) Changes in potential and kinetic energy negligible compared with changes in heat energy

From these assumptions the following equations can be derived for straight-through cooling:

$$\frac{\theta_{sm}-\theta_1}{\theta_2-\theta_1}=\frac{1}{r}=\frac{1}{2}\left[1+\sqrt{1+\left(\frac{\pi\eta}{St}\cdot\frac{A}{sL'}\right)^2}\operatorname{cosec}\left(\frac{\pi}{2}\cdot\frac{L}{L'}\right)\right] \quad (1)$$

$$\frac{\theta_{sm}-\theta_1}{\theta^*-\theta_1}=\frac{1}{r^*}=\frac{2-r}{r+\frac{r^2}{2}\cot^2\frac{\pi L}{2L'}} \quad (2)$$

The first corresponds to eqn (49) of a recent paper* but is expressed differently so that the experimental results and channel geometry can be inserted directly. The second equation gives the temperature of the coolant opposite the hottest point on the can, i.e. the temperature at which the heat transfer is most critical and therefore that at which the coolant properties are to be evaluated.

The assumptions enumerated above are now examined in order:

(i) This implies no out-of-channel leakage. The graphite structure design ensures that such leakage will be small.

(ii) Step-by-step calculations taking into account the variation of specific heat with temperature gave results agreeing within 1% of those from the simpler method, which was therefore retained.

(iii) This assumption is unnecessarily wide: it is sufficient to assume constant heat-transfer coefficient near the point of maximum can-surface temperature, provided that the heat transfer is not so poor elsewhere in the channel that the temperature there becomes limiting. One of the advantages of circumferential finning as opposed to longitudinal is that after a short entrance length the heat-transfer coefficient does not change with distance.

(iv) The form taken is that given by single-group neutron theory for a continuous bar of uranium. This form will be distorted to some extent by (*a*) the gaps between individual rods, (*b*) the return to the reacting core of neutrons thermalized in the end reflectors, (*c*) the non-uniformity of graphite and uranium temperatures along the channel, and (*d*) the partial insertion of control rods. Effects (*a*)–(*c*) are small and were neglected. It was assumed that the reactor would be run continuously at full power to secure maximum production, and that the initial reactivity would be adjusted to make this possible with the control rods fully, or nearly fully, withdrawn. A check showed that a small control-rod insertion, although distorting the flux distribution, has little effect on the maximum can-surface temperature because the rods are inserted axially from the hot end. Effect (*d*) was therefore also neglected.

(v) The mechanism of heat production is similar all along the channel, so the proportion from the graphite should be constant. A value of 7·4% from the graphite and 92·6% from the uranium is used.

(vi) Check calculations show that this can be done with negligible error.

* J. DIAMOND and W. B. HALL: "Heat removal from nuclear-power reactors," J. Brit. Nucl. Energy Conf., 1956, 1.

An example of a calculation is given in the Appendix.

Temperature distribution along the channel

Fig. 4 shows the variation of bulk-coolant, can-surface, and central-uranium temperatures along the channel. Note that during manufacture of the fuel element the can is pressurized on to the uranium rod. The high external pressure will maintain the two surfaces in good contact while in the reactor. It is therefore expected that the interface temperature-drop will not be large, and for simplicity in Fig. 4 the difference between the central-uranium and can-surface temperature has been taken as the drop in the uranium only.

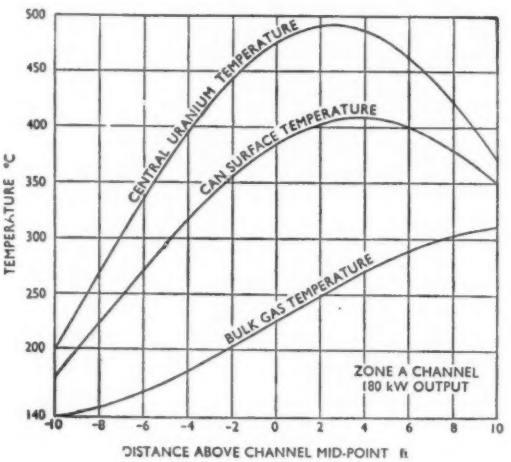

Fig 4 *variation of central-uranium, can-surface, and bulk-gas temperature along channel*

Pressure drop

The channel is split into three parts for calculation.

Entry (from bottom header to the beginning of the fuel elements)—The fuel elements are supported on a strut attached to the core support bearings and this carries a disc, known as a 'gag', to control the flow of coolant up the channel. When dealing with the whole core the selection of gag size becomes important, but when considering a single channel the minimum overall pressure drop is required, so the entry drop is found for the case where no gag is fitted. Experimental results of entry pressure drop from a rig simulating the channel-inlet geometry were expressed as the ratio of pressure drop from the bottom header to the beginning of the fuel elements, to the velocity pressure in the annulus between the gag and the surrounding cylinder. For each channel size they were plotted against gag diameter.

Fuel elements—Guggenheim's equation* was used to calculate the pressure drop over the length of channel occupied by fuel elements. Experimental curves of friction factor against Reynolds Number were available. It was found that the pressure drop caused by the fuel-element top-and-tail assembly was equal to that of the length of finned surface displaced. It was therefore necessary only to substitute the overall length of fuel elements for the total finned length.

Exit (from end of the fuel elements to the top header)—This comprises a parallel portion, and a divergent portion partly in the top graphite reflector and partly in the charge pan. It was treated conventionally.

Single-channel characteristics

For given inlet conditions, maximum can-surface temperature, and fuel-element design, the heat-transfer and pressure-

* E. A. GUGGENHEIM: "Compressible flow of perfect gas with heat input distributed symmetrically about the middle of channel," Canadian Atomic Energy Report No. 702, National Research Council, Canada, 1945, May; or see J. DIAMOND and W. B. HALL, op. cit, eqn (59)

drop calculations were repeated for a range of mass flows and for the channel sizes used in the experimental rig. Interpolation and extrapolation gave the results shown in Fig. 5.

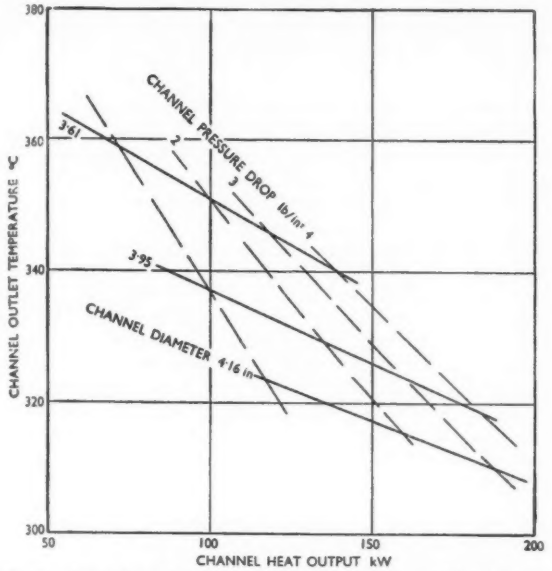

Fig 5 *channel outlet temperature against channel heat output with lines of constant channel diameter and constant pressure drop*

With the channel diameter, fuel-element design, and temperature and pressure conditions known approximately, a range of maximum channel heat outputs was chosen for which nuclear calculations were made.

The reactor coolant inlet temperature selected during the design study was 180°C. This was reduced to 140°C for Calder to secure increased heat output under the same limitations of blower power, pressure-vessel size, and maximum can-surface temperature. Further reduction was undesirable because of the resulting fall in steam pressures, and because the radiation damage to graphite was believed to increase rapidly at temperatures below that chosen.

During the design study, various channel lengths were investigated. A change in length had only little effect on the diameter of core needed for criticality under working conditions and on the channel heat output. The figure of 20 ft of uranium was chosen, and was retained for Calder.

Reactor core

Channel diameters

From nuclear calculations for conditions suggested by single-channel results, and from practical considerations, the core size and lattice pitch (8 in.) were chosen, defining the number of channels (1,696) and their positions. The next step was the selection of channel sizes. From Fig. 5 it can be seen that for a given pressure drop an increase in outlet temperature can be obtained by decreasing the channel diameter with the heat output. This also means a lower mass flow than if the channel diameter had been kept constant.

The channel heat-output distribution curves (Fig. 6) were prepared on the basis of a fixed reactor heat output. The most peaked distribution which it was thought would occur was that given by single-group neutron theory for a uniform core (curve (1)). However, it was felt that some enrichment of the uranium might be necessary to make the reactor critical at full power and temperature. An economical way of doing this would have been to load the channels in a central region of the reactor core with natural uranium and put slightly enriched uranium in the channels outside this region. This method gave the heat output distribution of curve (2).

The channel sizes therefore had to be selected to cover both cases, with the pressure drop available from the blowers. Any change of channel diameter was limited by the charging system to a change between charge groups, all 16 channels in one group being of the same diameter. This, and the arrangement of charge groups, lead to the conclusion that it would be worth using three different channel sizes in the zones shown in Fig. 7. It was also necessary for ease of charging to keep the channel diameter constant along a channel. For the innermost channel in each zone the greatest heat output was found from Fig. 6, and referring back to Fig. 5 the channel sizes were chosen for a given core pressure drop. They are 4·16 in. in zone A, 3·95 in. in zone B and 3·61 in. in zone C.

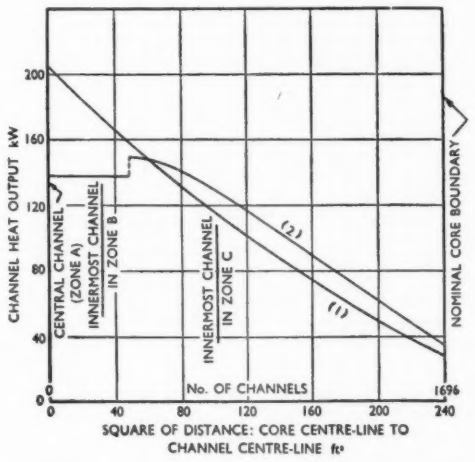

Fig 6 *channel heat output against position for flattened and unflattened cases*

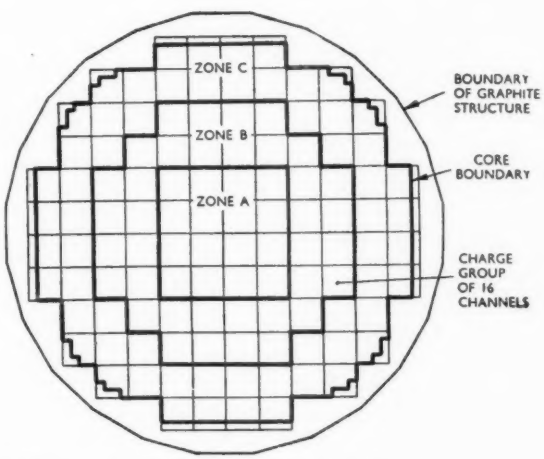

Fig 7 *arrangement of core zones, charge groups, and side reflector*

Channel flow control

To ensure a high bulk outlet temperature and economy in pumping power for a given heat output it is imperative that the relatively low (about 400°C) limit set on can-surface temperature should be approached in all, and not merely some, fuel-element channels. After choosing the channel diameters it was found that the design heat output could be removed between the inlet temperature of 140°C and the bulk-outlet temperature of 336°C if each channel was allowed just the

mass flow needed to make the maximum can-surface temperature 408°C. If no attempt at channel flow control had been made other than the use of the different channel diameters, the output and bulk outlet temperature would have been lower by about 25% and 60°C respectively with constant blower power. The combined effect on electrical power output would have been serious.

Even if the distribution of channel heat output across the core were invariable and known accurately, it would be difficult to control the coolant flow up every channel to that channel's exact requirements. It was decided to group channels for flow control purposes, all channels within a group having the same gag size and therefore taking approximately the same flow. Various schemes were considered with different numbers of groups and different arrangements of groups across the core. It was found best to have fewer channels in a group near the centre of the core than near the perimeter. With different numbers of groups it was found that the products (loss in heat output × number of groups) and (drop in bulk outlet temperature × number of groups) were constant at about 96MW and 174°C respectively, with constant blower power. It was considered practical to use 5 groups in zone A, 9 in zone B and 9 in zone C.

The channel sizes had been chosen on the basis of the reactivity estimates and heat-output distributions available at that time, but later when the gag sizes had to be decided there was more confidence that full power and temperature would be reached with the core entirely loaded with natural uranium. At the same time more refined calculations of heat-output distribution, taking into account the different channel diameters and variation of xenon poisoning across the core, became available. For the innermost channel in each zone the heat output (which was the maximum for the zone) was found, and thus the pressure drop across the ungagged channel. This pressure drop was the same for the innermost channel in zone A (i.e. central) as for that in zone B, but that in zone C was smaller. The velocities in the headers are small, so that the header-to-header pressure drop for all channels became equal to that for innermost channels in zones A and B in the ungagged state. All channels in the innermost flow groups in zones A and B were therefore left ungagged, and the gagging in the remaining 21 flow groups was chosen as described below.

The maximum heat output of a channel in a particular group was found. This gave the mass flow and the pressure drop from the beginning of the fuel elements to the top header. Subtracting this from the header-to-header drop gave the drop to be caused by that flow in the gag, and hence the gag size. The reduction in channel diameter from zone A through B to C made the gagging easier than it would have been with uniform channel diameter, for the small channels produce a greater pressure drop for given flow than the large, leaving less for the gag to produce.

Bulk outlet temperature

The bulk outlet temperature depends on the inlet temperature, total heat output, coolant specific heat and total coolant flow. The total heat output of the reactor is taken as the sum of that produced in the uranium fuel elements and the surrounding graphite. Heat is also produced in the pressure vessel and in the control rods, but in calculations these are regarded as cooling problems rather than as useful sources of heat.

For the fuel-element channels the mass flow through a channel in a particular group was multiplied by the number of channels in the group and the product was summed for all flow groups. This introduces a small error in that non-limiting channels in a group would have lower gas temperatures than limiting ones and therefore a slightly greater flow, but this was neglected. Holes were drilled through the plates forming the gas seal between the pressure vessel and the graphite to provide a flow of coolant up the annular space between the side reflector and the wall of the pressure vessel. Annular gaps were left between the restrictors and the impact stools at the bottom of the control-rod holes to allow some coolant up these holes. The flows from these three sources were added together and the bulk outlet temperature obtained.

Flattening the radial neutron-flux distribution

When the possibility of the core developing more reactivity than required was realized, the effect of using the excess to flatten the radial neutron-flux distribution was investigated. For the same maximum channel heat output this would have meant increased reactor heat output. However, at constant blower power (one of the design limitations) the maximum channel heat output had to be decreased as the flux distribution was flattened. This was mainly because the channel coolant flow had to be controlled tightly irrespective of the flux distribution, and partly because the channel sizes were chosen to cover the cases shown in Fig. 6, where both curves were drawn for the same reactor heat output. The net effect on reactor heat output was an increase that was small compared with the change in the ratio of the mean channel heat output to the maximum. It was therefore decided not to flatten the distribution.

General conclusion

New data and improved methods are constantly being used and the number of subjects on which calculations are needed is increasing. As a result much of the information obtained in the course of the work is now obsolete.

The two aims of the basic design were to achieve:

(i) A chain reaction under design conditions with natural uranium as the only fuel

(ii) A certain design heat output.

The reactor has now been operated such that it is quite certain that the first objective will be successfully met. In fact it has not been necessary to use any enriched uranium, but rather to replace some fuel elements by steel absorbers. The power output of the plant has been developed to a value close to the design, and it is most probable that the latter will soon be reached.

Appendix

Specimen calculation of mass flow, outlet temperature and channel heat output

Inlet temperature $\theta_1 = 140°C$ (284°F)

Maximum can-surface temperature $\theta_{cm} = 408°C$ (766°F)

Channel diameter $d_c = 4$ in. $= 0{\cdot}333$ ft

Fin tip diameter $d_f = 2\frac{1}{4}$ in. $= 0{\cdot}177$ ft

(Single-start helical fins 0·027 in. thick, at $\frac{1}{8}$-in. pitch on a 1·30-in. dia. can)

From experiments, $St = 0{\cdot}0099$ at $Re = 200{,}000$

In the test rig $k = 4{\cdot}86 \times 10^{-6}$ C.H.U/ft sec °C (air at 80°C)

and $k_m = 20{\cdot}7 \times 10^{-3}$ C.H.U/ft sec °C (magnesium alloy at 140°C)

$$\therefore Re\frac{k}{k_m} = 4{\cdot}70$$

$$s = \pi d_f = 0{\cdot}556 \text{ ft}$$

$$A = \frac{\pi}{4}(d_c^2 - d_f^2) = 00626 \text{ ft}^2$$

$$L = 20 \text{ ft}$$

Axial extrapolation length is taken as 1·8 ft each end

$$\therefore L' = 23{\cdot}6 \text{ ft}$$

$$= 0.926$$

Table I *lattice constants at the operating temperatures with natural uranium fuel and filled with carbon dioxide*

constant	core zone A	core zone B	core zone C	reflectors top	reflectors bottom	reflectors side
inner radius, ft	0	6·02	10·85	3·25*	2·67*	15·49
outer radius, ft	6·02	10·85	15·49	—	—	18·00
channel diameter, in.	4·16	3·95	3·61	—	—	—
no. of channels	256	576	846	—	—	—
Thermal utilization factor f	0·93186	0·93010	0·92672	—	—	—
resonance escape factor p	0·87533	0·87861	0·88398	—	—	—
fast fission factor ε	1·02972	1·02972	1·02972	—	—	—
thermal fission factor η_f	1·26595	1·26595	1·26595	—	—	—
multiplication constant k_∞	1·06330	1·06527	1·06789	—	—	—
radial diffusion area, cm²	406·6	391·9	371·1	7519·7	3765·1	3422·4
axial diffusion area, cm²	464·6	438·9	403·6	9340·7	4227·4	3422·4
radial slowing-down area, cm²	628·9	588·6	528·1	803·3	640·6	387·0
axial slowing-down area, cm²	709·5	652·7	570·6	962·1	703·2	387·0

* thickness of reflector quoted

Average uranium temperature = 425°C Average graphite temperature = 250°C

Substituting in eqns (1) and (2)

$$r = 0{\cdot}722$$
$$r^* = 0{\cdot}577$$

$\therefore$ Outlet temperature $\theta_2 = r(\theta_{sm} - \theta_1) + \theta_1 = 334°C$

and $\theta^* = r^*(\theta_{sm} - \theta_1) + \theta_1 = 295°C$

Table II *reactivity absorbed by steel rods loaded in place of uranium fuel elements in one channel at the centre of the reactor*

	one-group theory $\Delta k/k$	two-group theory $\Delta k/k$
channel left empty	0·00029	0·00014
steel equiv. to 1-in.-dia. solid rod	0·00192	0·00096
steel equiv. to 1·25-in.-dia. solid rod	0·00236	0·00122
steel equiv. to 1·5-in.-dia. solid rod	0·00273	0.00146
steel equiv. to ·75-in.-dia. solid rod	0·00305	0·00167

At 295°C $k = 6{\cdot}45 \times 10^{-6}$ C.H.U/ft sec °C

and $\mu = 17{\cdot}8 \times 10^{-6}$ lb/ft sec } for CO_2

Also at 408°C $k_m = 21{\cdot}8 \times 10^{-3}$ C.H.U/ft sec °C for the magnesium alloy

$$Re\frac{k}{k_m} = \frac{4W}{\pi(d_c + d_f)\mu} \cdot \frac{k}{k_m}$$

$$\therefore \text{Mass flow } W = \left(Re\frac{k}{k_m}\right)_{test} \frac{\pi}{4}(d_c + d_f)\left(\mu\frac{k_m}{k}\right)_{reactor}$$

$$= 1{\cdot}13 lb/sec$$

Enthalpy rise from 284°F to 633°F = 96·89 B.Th.U./lb

$\therefore$ Channel heat output $Q = 98{\cdot}1$ B.Th.U./sec

$= 103{\cdot}5$ kW

$= 54{\cdot}5$ C.H.U/sec

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2 MOORE and GOODLET on

The 1951-53 Harwell design study

IF DATES ARE IMPORTANT, 29 September 1950 could be taken as the day Calder Hall was conceived, although thinking at Harwell on these lines had been going on for some time before. On that day a Harwell conference examined the possibility of building a power-and-plutonium reactor to form the basis of a national scheme for nuclear power stations. Arising from this, Sir John Cockcroft gave the task of designing a natural-uranium power reactor to Richard Moore and Brian Goodlet and the design study started in January 1951 at Harwell.

By January 1953, the design for a 150MW heat 35MW electric (net) reactor for a burnup of 2,000MWD per ton had been completed and shortly afterwards authority was given for the Calder Hall plant to be built. The original design was known as PIPPA (Pressurized Pile Producing Power and Plutonium) and although much of the original concept was embodied at Calder, the final power station looked very different from the 1953 design. It has, for instance, two reactors and four turbines: PIPPA had one reactor, one turbine.

PIPPA had to be a natural graphite reactor, so the only possible moderators were graphite or heavy water. Graphite was chosen because D_2O would cost dollars and also seemed to present practical difficulties. Cooling by sodium or water would have meant more neutron absorption than could be tolerated without fuel enrichment, so the coolant had to be a gas. Carbon dioxide was chosen because it was readily obtainable at low cost and it was thought that all the compatability problems could be overcome. The gas had to be pressurized to reduce the blowing power and this meant the whole core had to be inside a pressure vessel. Thus the main features of the design emerged logically from essentially practical and economic considerations. Taking these features, PIPPA evolved as a 36 ft. dia. stack of machined graphite blocks inside a cylindrical pressure vessel with a 2 in. thick shell. The stack was about 27 ft high and was pierced vertically by about 1,700 fuel channels spaced on a rectangular 8 in. lattice. The actual core was 31 ft dia, with 2½ ft of reflector all round. The fuel rods were about 1 in. dia, 40 in. long, and there were to be five to a channel. This core would have developed about 144MW heat.

The coolant was pumped through the core by four motor-driven blowers and the steam was raised in four identical heat exchanger towers. Steam was raised at two pressures, and fed to a single turboalternator of 42·5MW rating. The following are the leading data of PIPPA.

Heat rate of reactor	143·7MW (= 490 × 10^6 B.t.u./h)
Volume of active core	15,100 ft³
Specific heat rate	9·5kW/ft³ (= 34,400 B.t.u./h ft³)
Maximum can temperature	752°F (400°C)
Coolant upper temperature	662°F (350°C)
Coolant lower temperature	356°F (180°C)
Coolant mass flow (max.)	6·5 × 10^6 lb/h
Steam conditions (Dual pressure cycle).	h.p. 400 lb/in² gauge, 625°F, 285,000 lb/h l.p. 130 lb/in² gauge, 625°F, 153,500 lb/h, 28·9 in.)Hg vac.
Gross electrical output	42·50MW
Blowing power	4·84MW
Other auxiliaries	2·30MW
Net electrical output	35·36MW
Overall efficiency	24·6%

Complete fuel charging schemes, control and instrumentation schedules and burst cartridge detection systems were worked out, much of which was subsequently used at Calder Hall.

The salient economic fact emerging from the PIPPA studies was that the capital cost per kW of a nuclear station would be

far higher than that of a conventional coal-firing one of comparable size. Nevertheless, taking into account the fuel costs, it was concluded that, even ignoring the value of the plutonium produced, the cost of nuclear power would be about 1d a unit: this was high compared with the average CEA cost, but 'by no means outrageous'.

The authors of this paper disclose that at Harwell in 1949 the 'possibility of early economic generation of power was not rated very highly'. It was thought that submarine propulsion was the 'only worthwhile application for some time to come' and a design study was commenced. Under Jack Diamond (now Professor at Manchester), a Harwell-Admiralty-Vickers-Metrovick team started work and conceived a helium-cooled, graphite-moderated design pressurized to 25 at. Work proceeded for two years but never reached the construction stage.

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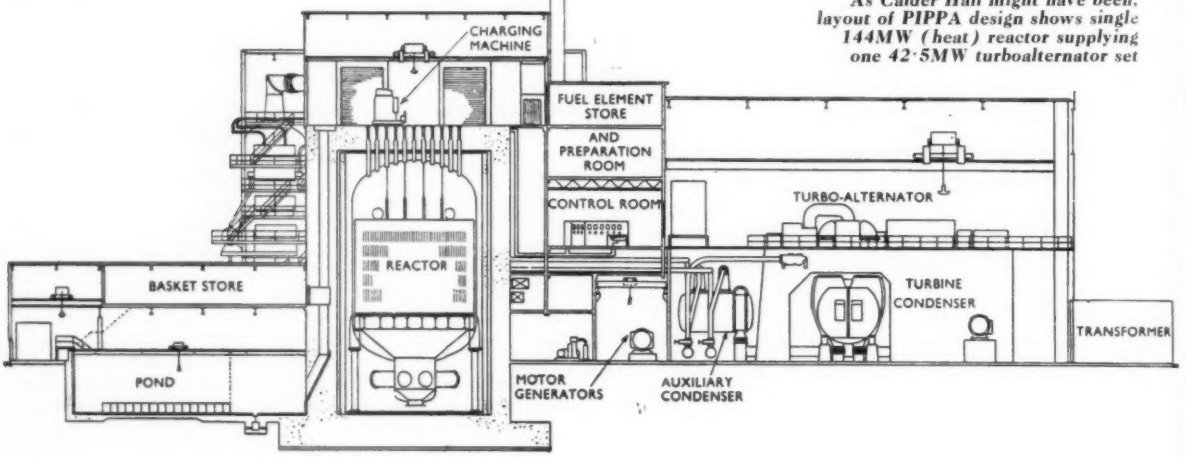
3 MOORE on

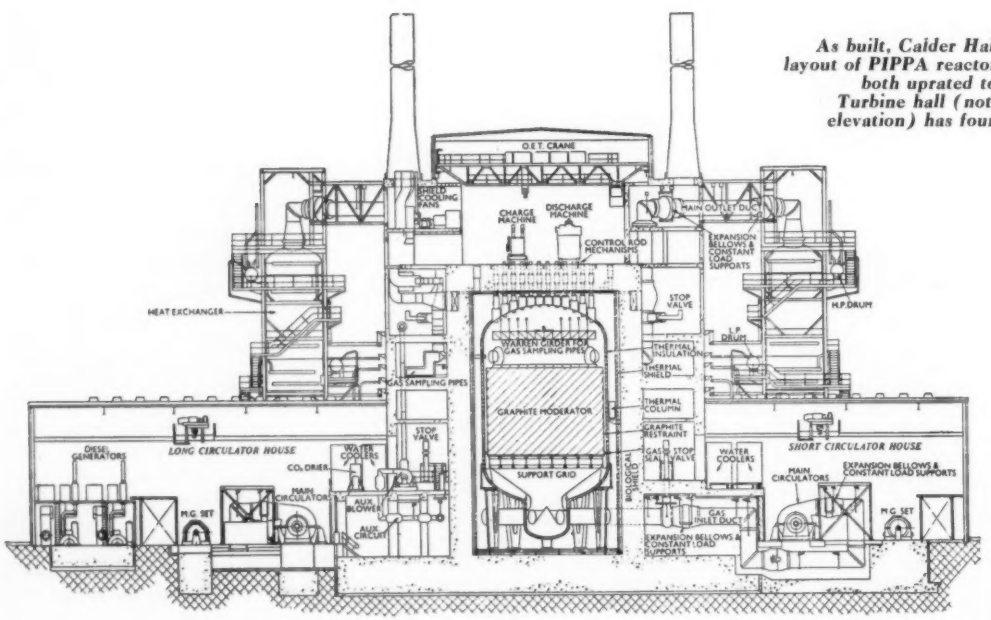
The design and construction of the plant

THE PIPPA study showed by the end of 1952 that the gas-cooled reactor was feasible and in February 1953 authority was given for the construction at Calder Hall of a single reactor. This was shortly followed by authorization of a second reactor. The emphasis was, however, now to be on plutonium production.

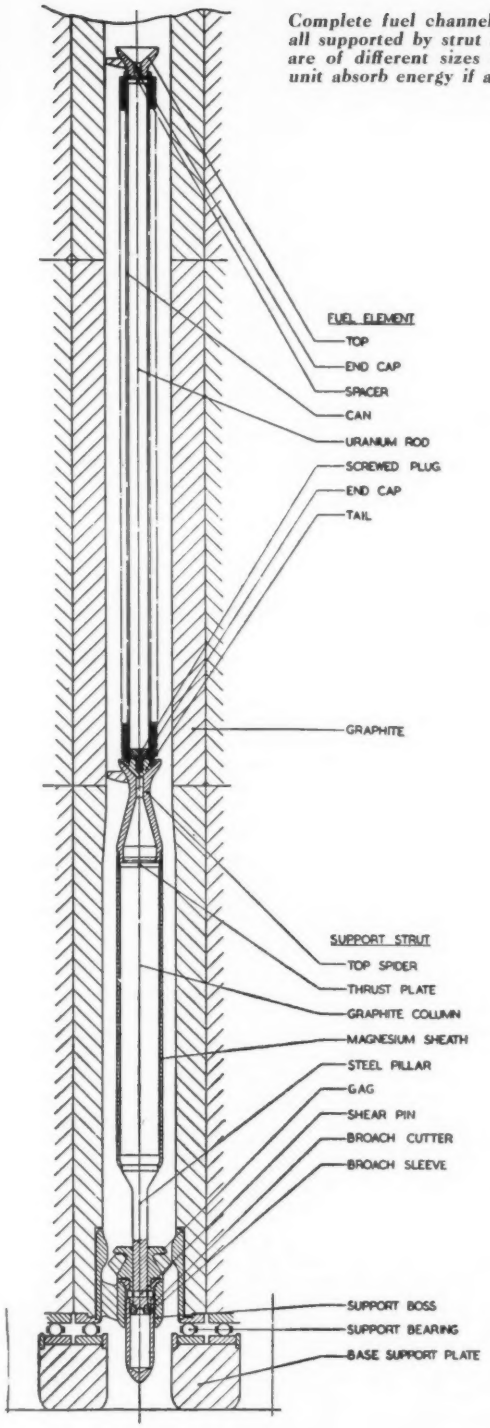
In core design, the Calder Hall reactors follow the PIPPA layout in general, although there are considerable detail dif-



As Calder Hall might have been, layout of PIPPA design shows single 144MW (heat) reactor supplying one 42·5MW turboalternator set



As built, Calder Hall retains general layout of PIPPA reactor but uses two—both uprated to about 200MW. Turbine hall (not seen in this end elevation) has four 21/23MW sets



Complete fuel channel assembly has six elements stacked one above the other and all supported by strut assembly transferring load direct to the base. Gags at lower end are of different sizes to regulate flow to each channel. Shear pin and broach unit absorb energy if a slug is accidentally dropped in

ferences. In the core, for example, the fuel elements were increased to six per channel and their length reduced to 40 in.

An interesting feature of the construction was the graphite block manufacturing facilities. The stack required about 60,000 blocks of some 270 different sorts. About 2,000 tons of rough bricks were machined accurately to size to give a product of about 1,200 tons. This was all done in a special workshop at Windscale and jigs and fixtures were used to give flow line production. Milling was extensively used and a considerable technique in graphite machining has been developed.

The method of supporting the fuel elements is noteworthy. The complete load in a channel of six cartridges is carried on a strut formed from a graphite column canned in magnox. At the top it has a female cone fitting to receive the male fitting of the lowest element, while at the bottom it incorporates a shear pin and broach unit. The lower end of the strut is supported directly by the core support grid through the bearings. The object of the strut is to protect the structure in the event of a grab failure while hoisting elements. If this happens, the pin shears and the broach is driven into a slightly undersize hole. In this way the energy of the falling element is absorbed. After such an incident the whole assembly would be withdrawn and a new one installed.

Referring to the CEA plants that are now soon to commence construction, Moore says 'they have virtually 10 years' accumulated experience behind them, and show every promise of being economic and reliable plants, now enabling nuclear energy to be used for the peaceful and useful purpose of providing heat, light and power to the community'.

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4 FORTESCUE and HALL on

Heat transfer experiments on the fuel elements

ONE OF THE MOST STRIKING developments in the story of Calder Hall was the discovery that circumferential fins on the fuel cans gave much better heat-transfer performance than the longitudinal fins hitherto used in the air-cooled British piles at Harwell and Windscale. 'At first sight' say Fortescue and Hall, 'such an arrangement seems quite unreasonable; it would be expected that the fin surfaces would not be swept by the coolant, and that the turbulence generated by the fins would lead to an excessive pressure drop. In fact, experiments proved it to be surprisingly efficient when compared with the longitudinal fin. It has since been shown that there is a systematic flow between the fins, generally in the form of two vortices.'

The performance of these elements was, however, not deducible from theoretical considerations and extensive experimental work was required to establish design data.

The reason longitudinal fins were rejected, was lack of mixing of coolant in a radial direction and experiments to promote this led to an unacceptable pressure drop in the channel.

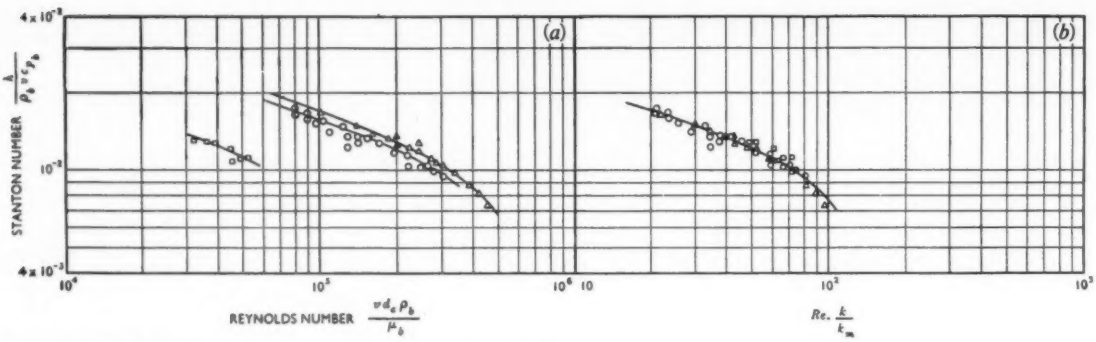
Experimental work used electrically-heated dummy elements. The basic problem is the same, because, as in a reactor, the heat release is independent of the temperature of the element and the electrical input could easily be measured.

The early experiments at Harwell used atmospheric air as the coolant but these were later extended to a pressure of 100 lb/sq. in.

Results showed that, varying the thermal conductivity of both the fin material and the coolant gas,

$$\text{Stanton number } S_t = \frac{h}{\rho V c_p} = \psi\left(R_e \frac{k}{k_m}\right)$$

where h = heat transfer coefficient, ρ = coolant density, V = coolant velocity, c_p = coolant specific heat (CP), R_e = Reynold's number, k = coolant thermal conductivity, k_m = fin thermal conductivity. The authors point out that this function relationship cannot be expected to apply to finned elements generally or even to transverse fins outside the range of shapes tested.



For tranverse-fin elements, curves (a) show effect of changing coolant conductivity. Plotting against Re (k/km) shows correlation of these results (b). Conductivity of can: k_m 0·3 cal/cm/°C/cm²/sec
Conductivity of gases: △ CO_2 0·000062; ○ N 0·000078; □ H_e 0·000415
Channel dia, 4 in.: Fin root dia, 1·36 in.: Fin tip dia, 2·125 in.: Fin thickness, 0·027 in.: Fin pitch, ⅛ in.

5 MUMMERY on

Experimental physics

THREE BASIC PROBLEMS have to be solved to provide the reactor designer with the information he needs.

1 The condition for criticality of the system must be evaluated as a function of composition and size of the system, of the concentration and disposition of the materials in the reactor and of the temperature and power at which the reactor operates.

2 Account must be taken of long-term effects due to the changes in the types of materials present resulting from neutron capture.

3 The dynamic characteristics of the system and the rate of heat production at all points of the system must be known as a function of the variables concerned.

The equation: neutron yield=neutron absorption+neutron leakage is the condition for criticality and it must be solved with great accuracy. An uncertainty of 2% in the neutron yield per neutron absorbed in U-235 would have led to an uncertainty of a factor 2 in the critical size of a reactor of the Calder type. This means that nuclear data used must be of the very highest quality and so a considerable amount of painstaking experimental work had to be done since much of it can only be obtained by practical laboratory work.

This was done by exponential and integral experiments. In the former, sub-critical piles were built in which the lattice pitch and fuel channel diameter could be varied. In this way, neutron distributions for differing boundary conditions could be studied and the buckling measured.

The integral experiments were carried out in a 5 ft cube of graphite blocks which took the place of the normal thermal column of the GLEEP reactor. In this way a flux of about 10^7n/cm²/sec was obtained and by it the average neutron flux in various materials in a lattice cell were obtained.

These experiments also established measurements of diffusion length to an accuracy of ½%. Allowing for known impurities in the GLEEP standard block, the absorption cross section of the carbon atom *in vacuo* was determined as 3·6±0·3 mb. A new value of the U-235 neutron yield of 2·03 was established by the use of revised nuclear data.

The fundamental properties of U-236 and the higher isotopes of plutonium are now fairly well established, but further integral experiments will be required. It is now confidently believed that an irradiation level of about 3,000MWD/t of natural uranium can be achieved at Calder.

6 HORTON and BONSALL on

Shield design

THE SHIELDING DESIGN was a joint effort of both Harwell and Risley and was aimed at the simplest and cheapest radiation protection which could be devised at the time. Since the work was begun in 1952 the amount of design data has greatly increased and many of the techniques used have now been superseded. But the general method of solution remains unaltered.

The maximum radiation dose-rate in the vicinity of the reactor was to be less than 1 maximum permissible level (mpl) in areas to which access was uncontrolled; higher levels were allowed in controlled areas. Concrete was chosen as the shield material because (1) it is reasonably efficient for both neutrons and gammas, (2) it is cheap and easy to fabricate.

Owing to the great complexity of the reactor systems as a source of penetrating radiation, many approximations were used to obtain solutions in time. For example, the core was taken as a flat slab and the gas mains were regarded as line sources. The work fell naturally into three main parts; radiation through the main shield, radiation from activation of the coolant, heat generation in the shield.

After preliminary calculations by extrapolation from existing reactors, the final shield computations were based on a two-group neutron analysis of the core. The emergent neutron spectrum was considered to be represented by 'thermal' and 'epithermal' neutrons in the conventional way.

Concrete is a relatively poor gamma shield compared with the performance as a neutron absorber. The gammas arise from fission and also from neutron capture in the reactor, pressure vessel, thermal shield and biological shield. The radiation flux at the exterior of the 7 ft-thick shield is given in Table I.

A major difficulty was the calculation of radiation streaming through the holes in the shield which carry the gas ducts. This could have been scattered by using many bends and baffles in the ducts but for reasons of pumping efficiency, this device was limited to the use of two right-angled bends.

The main activation of the gas are the isotopes A-41, O-19, and N-16. The half-lives are 110m, 29·45s and 7·55s respectively. At Calder, the time to traverse a whole gas circuit is about 20s. The argon activity therefore remains nearly constant. The nitrogen activity decays very quickly but the radiation is no less than 6·1 MeV—one of the most energetic gamma rays known. Activity from O-19 and N-16 is therefore much higher at the gas outlet than at the inlet. The calculated dose-rates at various points in the circuit are given in Table II.

thermal neutrons, $n/cm^2/sec$	gamma radiation, mr/h, from neutron capture				fast neutron flux, $n/cm^2/sec$	total radiation flux
	graphite	pressure vessel	thermal shield	concrete		
negligible	0.04	1.3	2.1	2.1	negligible	5·5 mr/h (=0.73 mpl)

Table I *radiation flux at exterior of shield*

position in circuit (2 ft. from surface)	dose-rate, ^{41}A	mr/h, ^{16}N	due to ^{19}O	total dose-rate, mr/h
reactor exit pipes	19	48	2	69
top of heat exchangers	2	8	0.2	10
Bottom of heat exchangers	3	6	0.2	9
reactor inlet pipes	26	23	2	51

Table II *calculated dose-rate levels at points in cooling circuits*

The mpl is 7·5 mr/h, so access to these areas is strictly limited while the reactor is running.

Calculations of the heat distribution show that the maximum rise in temperature in the 7 ft thick concrete shield would have been about 13°C without a thermal shield: with 6 in. of steel interposed, it was reduced to about 2°C.

8 HUDDLE and WYATT on

Early metallurgical problems

ONE OF THE most striking developments that helped to make Calder Hall was the discovery of the *Magnox* material. Uranium is attacked by air at quite low temperatures and above 350°C the reaction is self-sustaining: with CO_2 the attack is less severe, but not negligible. The fuel rods have therefore to be canned. Uranium alloys with most metals at high temperatures but Harwell tests in the period 1951-3 showed that magnesium did not have this property—even under irradiation. Its absorption cross section ($N\sigma$) was only about one-fifth that of aluminium and it was therefore strongly indicated as a canning material. With commercially pure metal the corrosion resistance in dry CO_2 was good but if the gas had any moisture in it the resistance was markedly lowered. This was, however, improved by alloying with zirconium.

One uncertainty was the fire risk. This is not great in CO_2 but it was felt that the more oxidation resistance that could be built into the alloy the better.

Consideration of certain theoretical aspects of metal diffusion suggested that beryllium might prove the answer and in cooperation with Magnesium Elektron Ltd a series of alloys containing Be, Ca and Al in standard grades of pure Mg were produced. These showed great superiority over the pure metal and tests in wet CO_2 of one alloy showed no oxidation failure after 2,500h at 615°C. These alloys were named *Magnox* (MAGnesium No OXidation). About 60 of these alloys were produced, composition of a typical one—Magnox E—being 1% Al, 0.05% Be, 0.1% Ca in 99.95% pure Mg. Even on melting, these alloys are protected against combustion by the formation of a protective sheath. A further value of Magnox is its resistance to corrosion in water. This is important because on removal from the pile the slugs are stored in a cooling pond for a considerable period.

Further tests on Magnox's showed that some were prone to weld-cracking during can fabrication and it was discovered that the calcium should be kept below 0.05% or omitted altogether. Aluminium should not exceed 10%. Further Magnox developments took place at Risley, although the Harwell work established principles for fabrication and end sealing. For example, it had been decided that the cooling fins should be circumferential and not longitudinal and trials showed that thread rolling by the *Integron* process could not produce them high enough or sufficiently thin. Cans were therefore machined from bar. Thick walled extruded tubing was tried but the bores could not be obtained straight enough.

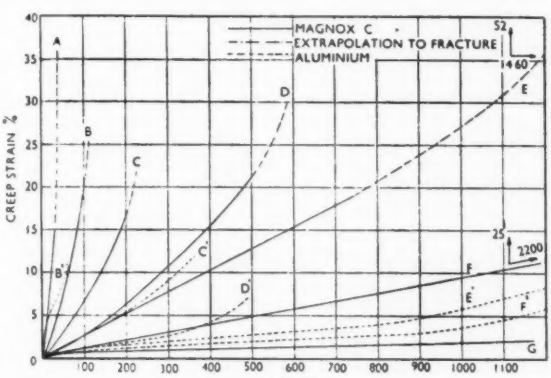
9 GRANGER and McINTOSH on

Metallurgical developments

ALTHOUGH MOST OF the early work on fuel elements was done at Harwell, when the project was transferred to Risley there was still intense development work to be done—not only to devise a completely productionized element but also to set up a complete manufacturing organization (each reactor carries over 10,000 elements). An early decision was to alter the PIPPA fuel support system from five 4 ft elements in a channel, each supported individually, to six 40 in. elements stacked one on top of the other. Separate supports were not considered reliable and 4 ft was thought too long to prevent bowing under heat.

Vacuum casting of the bars into graphite moulds was chosen and development produced a mould with a considerable life. Chromium-plated steel moulds are now known to be suitable. Heat treatment for grain refining and randomising is carried out in h.f. ovens. This has to be done quickly to prevent oxidation and precautions have to be taken to maintain straightness.

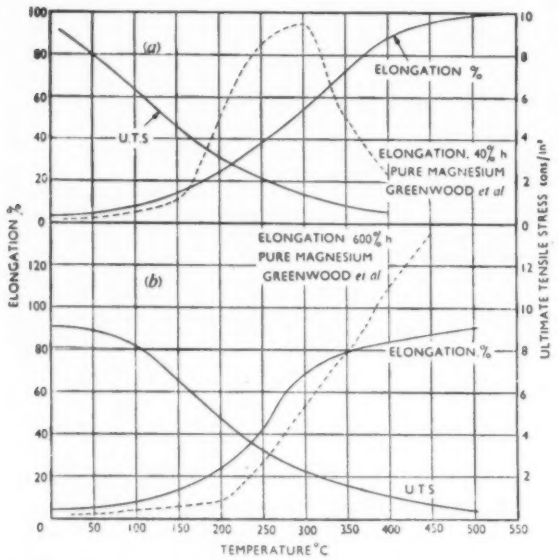
Further work on the Magnox alloys was carried out and included corrosion tests in CO_2 with varying amounts of moisture. From these, Magnox C emerged as the best alloy.



Creep curves for **Magnox C** *and Aluminium. Stress values, t/in²:* **Magnox C.** *A-·4, B-·35, C-·30, 0-·25, E-·20, F-·15, G-·10*
Aluminium: B'-·45, C'-·40, D'-·35, E'-·30, F'-·25

Tests in dry CO_2 at 8 at pressure gave an oxidation rate of 0.1 mg/cm²/5 months. Magnox C contains no calcium because its presence tends to cause weld cracks.

The principal problems of assembly included sealing, pressurizing, helium filling and cleaning. These had to be solved



Tensile-temperature properties of **Magnox C** *with strain rates: (a) 18%/h, (b) 1075%/h*

for a full-scale production line. The helium is introduced as an inspection device, any leaks in new cartridges being detected by mass spectrometer. This technique had already been established for the Windscale cartridges.

With the object of keeping the situation under constant surveillance, a Fuel Element Analysis Section has been formed.

As at Harwell, considerable research was also undertaken on steels—particularly those for the pressure vessel and an extensive programme of CO_2—compatibility and creep testing was carried out on mild and low-alloy steels.

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10 BROWN, NOONE and BISHOP on

Design and construction of reactor vessel

THE MATERIAL USED for the Calder reactor pressure vessel had to be corrosion-resistant to CO_2, have good creep properties up to 725°F and yet be as free as possible from the danger of brittle fracture during site fabrication. A low-carbon mild steel was chosen after consideration had been given to stainless and stainless-clad steels.

The steel used, *Lowtem*, is supplied in the normalized condition and has the following specification: 0·12–0·16%C, 1·00–1·20%Mn, 0·045(max)%S, 0·045(max)%P, 1½ lb/ton Al addition, 26–30 ton/in.² UTS, 35 ft-lb Charpy Impact at 14°F (average for 3 test plates).

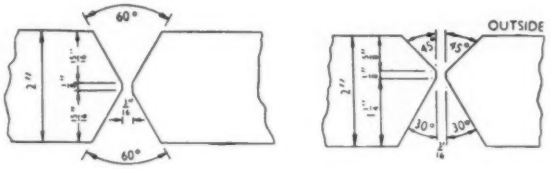
The figure shows the superiority of *Lowtem* over ordinary mild steel on Charpy impact test.

Whilst experience at that time was limited the pressure vessel designers had had considerable experience in the site welding of steel similar to *Lowtem* in thicknesses up to 2 in. and in other steels up to 2½ in. The figure of 2 in. was chosen as a feasible thickness.

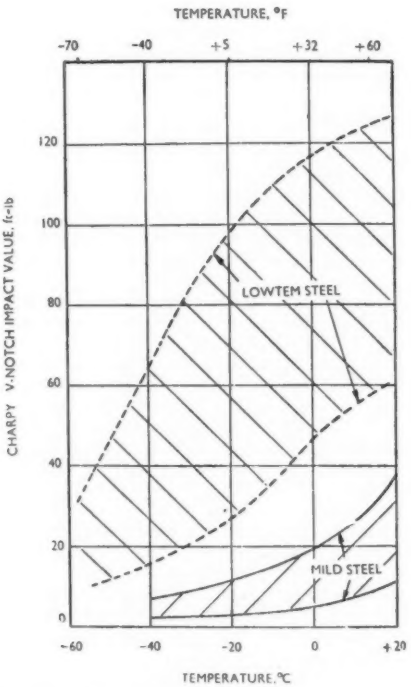
Experience in large pressure vessels and wind tunnels led to the choice of a design stress of 12,000 lb/in.² at the design temperature of 400°C with a joint factor of 0·95, necessitating full X-ray of all butt welds and stress relief of the finished vessel.

The rate of corrosion of the pressure-vessel steel in contact with dry CO_2 at 100 lb/in.² gauge and 752°F is, according to the latest experimental work equivalent to a depth of attack of 0·0002 in. in 6 months and 0·002 in. in 20 years. The scale formed is tightly adherent unless rust is allowed to form in a normal damp air atmosphere before the CO_2 tests.

The design study showed that trace amounts of cobalt, with its long half-life of 5·3 years would in time give an activity level which would preclude maintenance by *normal* methods. An exhaustive search was made, without success, to find a steel with no cobalt content. All had trace amounts present. For normal steels, a content of 0·015 to 0·020% appears to be unavoidable unless special selection of the ore is made, when 0·005% could be achieved.



Typical weld preparations: (l) domes, (r) vertical seams in shell



Improved impact values of **Lowtem** *compared with mild steel*

Two long-term creep tests were done at the Culcheth Laboratories of the UKAEA, using a stress of 11,200 lb/in² at a temperature of 716°F. After 15,000 hours, the creep rate is still decreasing, the total creep strain at 100,000 hours being estimated to be 0·18%. Whessoe tests, which were terminated at 4,500 hours, were in agreement with the Culcheth tests.

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11 DENT and GROSSMITH on

Uranium fuel handling

THE CALDER HALL REACTOR has to be shut down and depressurized for fuel changing. The possibility of charging and discharging on load was considered, but the mechanical complication was considered to belong to the next stage of development and so it was decided that Calder would change large quantities of fuel at infrequent intervals rather than 'little and often'. This meant that no mechanisms or moving parts need be inside the pressure circuit.

General features of the system have already been described in these pages (NUCLEAR POWER October). Briefly, for fuel charging, the 1696 fuel channels are grouped into 16's (4 × 4). In the centre of the group of 4 in. holes is a smaller one, known as the x-hole, into which a control rod may be introduced. The whole of the top of the graphite structure is covered by square cast-iron plates each one containing 16 tapered holes leading into the core channels and one for the x-hole. This is known as the *charge pan* and is intended to prevent the core holes from damage.

Above each group of 16 channels and coaxial with the x-hole, is a vertical charge tube ending in a flange on the charge floor. Through these tubes, the elements in the 16 channels are placed and removed by means of specially designed charge machines which pass the cartridges up and down a chute which can be accurately positioned over any particular channel.

The whole fuel handling system is of considerable complexity and ingenuity but since it is unlikely to be used in future reactors (apart from Calder B and Chapel Cross) it will not be described in detail. It may however be mentioned that a special television camera with an overall diameter of only 3½ in. was developed by Pye Ltd to examine the inside of fuel channels.

12 BOWDEN and MARTIN on

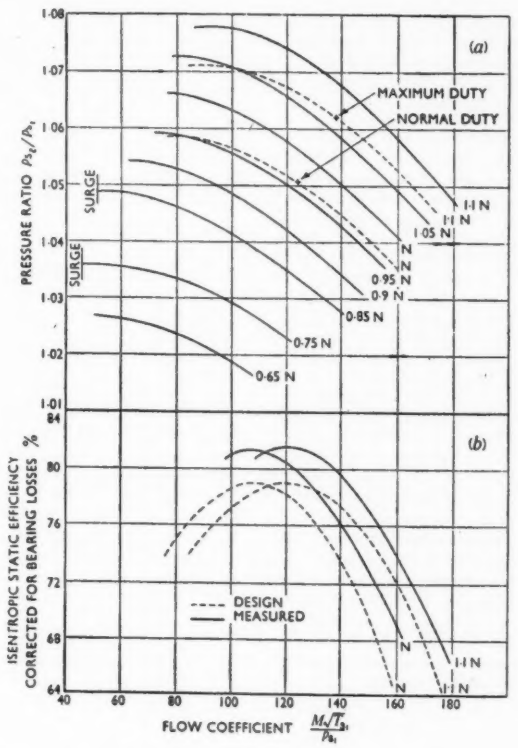
Design of important plant items

THE FIRST PART OF THIS PAPER describes the steam turbines and associated plant; the second, the gas blowers and ducting. The following table gives details of the blowers; their characteristics are shown in the figure:

	normal	maximum
mass flow of CO_2 through reactor, lb/sec	1964	2160
mass flow in each of four circulators, lb/sec	500	550
circulator outlet gas pressure, lb/in² abs.	115	115
circuit pressure drop, lb/in²	5.63	6.69
compression power, bhp	1497	2000
mechanical losses (estimated), bhp	45	55
power at motor coupling, bhp	1542	2055
speed, rev/min	854	940

The outstanding design difficulty was the evolution of a shaft seal to minimize leakage and yet provide reliability in service. One requirement was that if possible the seal had to be renewable without depressurizing the circuit. This is done by using two seals—an oil pressure seal for normal running and a special standstill seal which is operative only when the impeller is stationary. The pressure oil is supplied through a bellows-operated oil/gas differential pressure control valve at a mean pressure of 5 lb/in.² above the gas pressure. Most of the oil flows outward: the small amount passing inward drains to a pressurized detraining tank, after which it is degassed and used again. A labyrinth gland is fitted between the oil seal and the impeller casing. This provides some resistance to flow in the event of a failure of the inner seal ring. It also prevents back-diffusion of oil vapour into the gas.

The standstill seal operates by jacking the whole impeller shaft by the thrust adjusting gear until a metal to metal contact is made between the shoulder of the impeller and the casing, the joint being made gas tight by a silicone rubber seal. Once this is done, the gas pressure on the rubber provides a tight seal, allowing the running seal to be withdrawn.



Blower curves. P_{s1} — inlet static pressure lb/in.² abs:
P_{s2} — outlet static pressure lb/in.² abs:
M — mass flow lb/sec: T_{s1} inlet static temperature °F abs

In the event of an a.c. failure, the impellers can be driven at 100 rev/min by a pony motor run from the guaranteed d.c. supply. This speed is sufficient to provide circulation for the shutdown condition.

Design of the gas ductwork provided many problems of mechanical design owing to the necessity of catering for considerable thermal expansions whilst maintaining complete freedom from leakage. At the same time, the pressure drop in the ducts had to be kept as low as possible.

The ducting was considered as rigid links with joints at the bellows expansion units, the angular displacement of the joints being a function of terminal movement of the vessels and the expansion of the direct lengths themselves. Where flexibility in more than one plane was required, a gimbal type of bellows construction was used.

The bellows were made from steel having an u.t.s. of 26-30 ton/in.² working to a maximum allowable stress of 14 ton/in.², and to ensure stability the maximum number of corrugations per unit was limited to 14. In the design stage, model tests were used. Each finished assembly was fully tested.

13 WOOTTON on

Steam-cycle analysis

AS ADVANCES in nuclear technology provide higher gas temperatures, the triple-pressure cycle for the steam turbine will certainly be given serious consideration. This is sensitive to coolant outlet temperature and modest improvements can bring rapid increases in overall efficiency. It is expected to be economically competitive with any other cycle however high the permissible fuel temperature may be raised.

Studies of steam cycles by Babcock & Wilcox were started a long time ago and much of the background had already been completed by 1948 in collaboration with Harwell. This work, which covered single, dual and triple-pressure cycles, feed-heating, reheating and even thermocompression, proved invaluable when the idea of a British power reactor was revived again in 1951.

Taking a given temperature of the hottest fuel element, a wide range of thermal outputs is possible and the ultimate design was chosen on economic and practical considerations, it always being borne in mind that Calder Hall had to produce as much plutonium as possible.

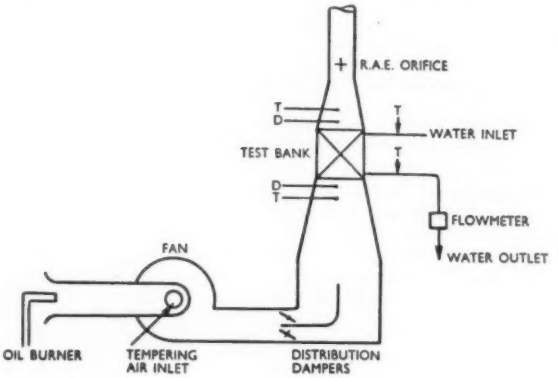
The dual-pressure cycle was preferred to the single because the net result was a greater net electrical output (gross output, less blowers) at a cost per kW installed appreciably lower. It was more complex, but had the advantage that it lent itself to a system of control by which undesirable temperature transients in the reactor structure under conditions of changing load can be minimized.

Feed heating was rejected because it led to lower steam pressures. Reheating in the single-pressure cycle was found to have no theoretical or practical advantages over the dual-pressure. This was due partly to the pressure losses in the long pipe runs, the higher pressures obtainable in the dual cycle and the non-availability of the duel-pressure control system. Much the same argument militated against reheating the dual cycle. The triple pressure cycle looked attractive but was rejected largely because of additional complications.

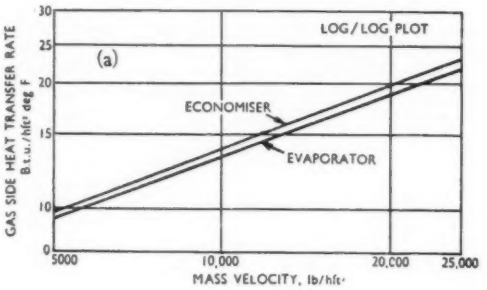
14 MORRIS and WOOTTON on

Design and construction of heat exchangers

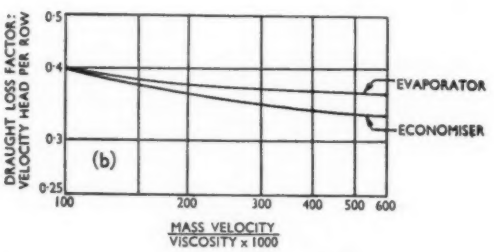
TO PROVIDE the necessary heat-transfer surface economically the use of extended surfaces was essential. It was decided, therefore, to use elliptical studs electrically welded to the tubes. This application required the extrapolation of existing design data beyond the limit considered advisable and so a test rig was constructed, in which both heat-transfer and pressure-drop characteristics could be determined experimentally. In this rig, hot gas was passed across various arrangements of tubes carrying water. By burning diesel oil in the suction of the fan, hot gas was generated which passed over the tubes and up the chimney. The heating surface which could be accommodated in the rig amounted to some 600 ft² and gas flow-rates of up to 20,000 lb/h ft² with thermal duties of the order of 1×10^6 B.t.u./h were employed with mean temperature differences ranging from 100 to 150°F. The overall heat-transfer rates obtained were corrected for internal water-flow transmission and for tube-wall transmission, assuming a uniform heat flow through the tubes. Draught loss results were expressed in fractions of velocity head loss per row, based on arithmetic mean gas temperatures and mass velocity in the minimum free area. The curves developed for the selected arrangements of evaporator and economizer tube banks are shown in the figure. The data from these curves were used in conjunction with the conservative figure of 2,000 B.t.u./h ft² °F for the heat transfer to boiling water when calculating the evaporator surfaces, and the formula from McAdams (*Heat Transmission*, McGraw-Hill) when calculating the inside heat-transfer rates for the economizer. Results from Pierson and Grimison (*Correlation and utilization of New Data on Flow Resistance and Heat Transfer of gases over Tube Banks*. Trans. A.S.M.E. Oct 1937) were used for the heat-transfer calculations associated with the outside surfaces of the superheaters, whilst the formula from McAdams was used for the inside.



Heat exchanger elements were tested in a simple test rig using fuel oil as heat source



Overall heat transfer rates for stud tubes chosen



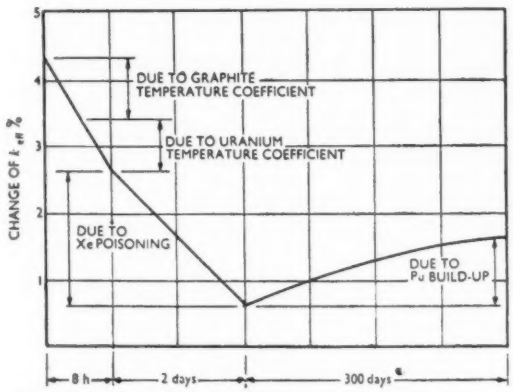
Draught loss curves for the same arrangement

15 GHALIB and BOWEN on

Equipment for control of reactor

THE VARIATION of k_{eff} for the Calder reactor during about a year's operation without a change of fuel is shown in the figure. The minimum control rod capacity had to be designed to cope with these variations at all times and also provide a margin for contingencies including emergency shutdown.

The rod system provides a maximum rate of release of reactivity of 2×10^{-6} % per sec with all rods moving together. A group of rods is however set aside for fine control and they have a maximum effect of 0·2% on k_{eff}. For shutdown, the rods may be inserted at 4 ft/sec, with a mean acceleration of 2 ft/sec^2.)The rate of change of k_{eff} is about 1% per sec.



Available reactivity drops rapidly during first two days, then recovers due to Pu build up

The control rods are about 22 ft long, of 1¼ m. dia. 18/8/1 stainless steel tube with low cobalt content. The absorbing material is boron-steel alloy made in the form of short tubular inserts. These are of two alloys—4% and 3%. The higher alloy tubes have ¼ in. thick walls and are placed near the bottom of the rods, because they are more often in the core. The upper part contains the 3% alloy in ⅛ in. walled tubes. At the top, the cables to the actuators are attached to the rods in such a way that their removal from a remote position is relatively simple. A spring shock absorber is incorporated the head and the rod is supported by the charge pan when in the lowered position. Should the cable break, the impact on the charge pan is limited to 300 lb. by shear pins and the kinetic energy of the falling rod is absorbed at the bottom end by a broach unit similar to those used on the fuel element struts. The paper also describes the actuator units.

16 LONG, LAITHWAITE and CUNNINGHAM on

Detection of faulty fuel elements

AFTER REVIEW OF six possible methods of detecting punctured fuel cans, the wire precipitator method was chosen as offering the most practical and reliable system. The authors remark, however, that because Calder Hall is the first reactor of its kind the system used is 'somewhat more comprehensive and flexible than may be found necessary in operation. Subsequent industrial designs will probably be more simple and economical'.

The system has already been described at some length in these pages but this paper fills in a considerable amount of detail.

The main isotopes used in detection are rubidium and caesium formed from krypton and xenon fission products. It is the beta-particles from the subsequent decay of these two isotopes which provide the signal indicating a can burst. The argon atoms passing the filters decay quickly to a stable isotope of potassium and so give no signal. It is this feature which discriminates against the spurious count from argon impurity in the coolant.

With an optimum 'soaking period' in the precipitator unit, the exposure of 1 square millimetre of uranium at the centre of the core will give 128 counts/sec with a 100% efficient counter, the count varying directly with efficiency.

17 COX and SANDIFORD on

Reactor control and instrumentation

SOME OF THE INSTRUMENTATION at Calder Hall is novel and in some cases it was developed specially for this plant. A number of complications were encountered because of the pressure vessel, and instruments located therein had to be able to withstand continuously elevated temperatures combined with a high level of neutron and gamma irradiation. Such equipment is very difficult to maintain or replace and the necessary gland seals require careful design.

For the reactor, the following groups of information are required:

1 rate of heat production
2 operating conditions of coolant circuits and hence heat-removal rate.
3 generating conditions of steam and hence heat utilization rate.

In addition, the operator must have information to enable him to avoid overheating important components.

Rate of heat production is estimated from the fission rate obtained from neutron flux measurements taken from subcritical to full power. This is done by ionization chambers in a block of graphite 8 ft wide, 5 ft 4 in. high and 2 ft 2 in. thick placed outside the pressure vessel about half-way up the core. This acts as a thermal column and thermalizes fast neutrons escaping from the core, providing a flux of about 3×10^5 n/cm^2 sec at full power.

When the reactor is shut down the only source of neutrons would be from the spontaneous fission of the uranium and this would represent only about 0.4 milliwatts, or 2×10^{-12} of full power. This would only give a thermal column flux of 6×10^{-2} n/cm^2 sec which is far too low to measure accurately, so four antimony-beryllium sources are placed in the reactor. These consist of a tube of beryllium metal into which antimony is cast, the whole being encased in stainless steel. While the reactor is running, Sb-124 is produced from Sb-123. This is gamma-active and it produces neutrons by a photo-neutron process in the Be. When the reactor is shut down, these sources give rise to a neutron power of about 2W which raises the neutron flux in the ion chambers to about 30n/cm^2 sec. This is adequate for the $^{10}BF_3$-filled proportional counters of the pulse counting equipment. The Sb-Be sources are reactivated while the reactor is running and absorb about 3×10^{-4} in reactivity.

The ion chambers used are the type RC1 which is one of a series embracing a wide range of sensitivity developed specially for Calder Hall. These chambers are surrounded by lead shielding in order to attenuate the strong gamma background coming from the Mn, Fe and Co in the steel pressure vessel.

This paper also describes the instrumentation of the gas and steam circuits and the many safety measures adopted.

18 ANDERSON and BOWEN on

System control and protection

THE CALDER HALL PLANT, when both reactors are working, will need a shift staff of 40, including six on routine maintenance. In charge will be a Shift Engineer, with an Assistant Shift Engineer responsible for the two reactors and their two gas circuits, and another responsible for the steam and electrical systems. In each reactor building is a Control Engineer in charge with one Plant Attendant in the Control Room and one in each circulator house. A third Control Engineer mans the electrical control room, whilst a Foreman Turbine Driver takes charge of heat exchangers and turbines, with one Senior and one Assistant Driver for two sets, and one Assistant per pair of heat exchangers.

The reactor is controlled manually, but provision is made for an automatic system should it be desired. The paper describes fully how the plant is started from cold, how it is controlled and how it is shut down. Its behaviour under all possible fault conditions is detailed and procedures for dealing with them are outlined.

1 HINTON on

The place of the Calder Hall type of reactor in nuclear power generation

REACTORS OF THE CALDER HALL TYPE—but much improved—will still be built 25 years from now, although in the second half of the period it is likely that in certain land-based applications reactors of higher rating will be replacing it. Improvements can, however, only be taken to a certain point: to get further, we must achieve the higher ratings that are possible only by the use of liquid coolants. This is not practicable in this country at the moment because: they involve technological problems which we have not solved yet; they demand materials which are not in commercial supply yet; they need enriched fuel, of which we have insufficient to spare. In time, these problems will all be overcome and highly-rated liquid-cooled reactors will become available. At first they will go to those willing to pay inflated prices for reduced specific weight: later they will become normal industrial equipment.

While we must put all we have got into developing the graphite-moderated gas-cooled reactor to obtain what is immediately practicable, we must press forward these other systems which at present are not industrially attractive.

Calder Hall has given us the initial lead in the use of nuclear power and we shall retain that advantage for at least a decade by improvements. In the long term we shall only maintain the lead if we develop higher-rated reactors. This is what the UKAEA are doing at the moment.

Calder footnote

MUCH HAS APPEARED on Calder Hall in the pages of NUCLEAR POWER during the last three months: as a postscript, it is interesting to read an overseas opinion on the plant. Here is the American journal NUCLEONICS commenting editorially in its October issue:

Apart from the achievement of an historic 'first,' special plaudits are due the British for what lies behind this accomplishment. Although they worked hand-in-glove with the US throughout the Manhattan Project, the legislation we passed after the war forced them to go it alone. They got absolutely no assistance from us on the building of their production reactors, and their gaseous diffusion plant. And they certainly got none on their new dual-purpose reactors.

Thus, a hard core of brilliant scientific and engineering talent had to start from scratch in 1946 and develop a knowledgeable atomic energy organisation. That they did this there is no question. But those who have not had the opportunity to visit the UK Atomic Energy Authority establishments may not be aware of the single-mindedness of purpose and the esprit de corps *that exists among the personnel.*

It was this more than anything else that enabled the AEA to finish the Calder Hall twin-reactor station three years from the time of groundbreaking, despite, among other things, the generally cool reaction that the gas-cooled reactor concept has received in the U.S. Where the British go from here depends very much on the engineering experience they develop. Although they are certainly not wedded to the gas-cooled type, they expect to wring the utmost from it. It is already clear that the bids due this month (Oct 1st, ed.) from British firms on the first gas-cooled power-only stations will represent a vast improvement in design over that of the Calder Hall Station.

The British still have a lot to learn. And so does the US. But it is nice to know that at last the world has full-scale operating nuclear power stations on which to cut its teeth.

Our thanks to the United Kingdom for that!

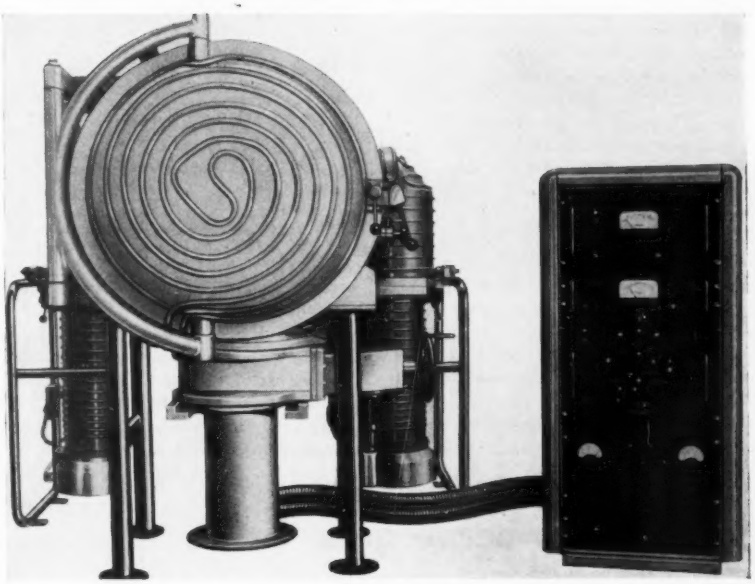
Flexibility, versatility features of Via-Vac furnace

The new *VIA-VAC* F.25H high vacuum furnace produced by Vacuum Industrial Applications Ltd, has been designed to melt and cast or sinter metals at low pressures, using resistance or high frequency induction heating. Due to the flexibility and adaptability of this new model, the equipment can be used for a large variety of applications in the field of vacuum metallurgy.

Latest developments in this field have laid emphasis on two main demands:
1 Operation, for the purification of metals with the charge hot, at pressures below those of dissociation of the oxides.
2 Quick access to the mould without the danger of thermal shock to the crucible or the loss of time to permit adequate cooling.

The new *VIA-VAC* range is designed to satisfy these demands and introduces a large number of features which add to the efficiency of operation and quality of product. Provision of an adequate pumping system, which forms the basis of the plant, together with a variety of interchangeable chamber fittings, gives scope for rapid conversion to meet special needs.

The vacuum work chamber is fabricated from mild steel with an internal polished stainless steel cladding and has a 30in. internal diameter. The crucible has an internal diameter of 6in. and height of 12in. Taking the packing factor as 1·5, a charge of 25 lb of steel can be accommodated. In order to provide facilities for additions to the melt, a number of charging buckets can be accommodated within the work chamber. Additions may be made at will by the operation of an external selector mechanism.



The Via-Vac F. 25H high vacuum furnace can be used for continuous production. Heating is by resistance or high frequency

To permit continuous production, facilities are provided for adding charges to the crucible through a vacuum lock. If required, inert gases can be introduced and pressure maintained at a prescribed value by the addition of a needle valve on the work chamber.

All high vacuum valves incorporated in the equipment are power operated and controlled from rotary switches located on a graphic display panel within the main control rack. All controls are mounted on GPO standard pattern panels, accommodated in a 4 ft. totally-enclosed control cabinet.

Pressure measurements at various points in the system may be taken by means of ionization and thermocouple gauge heads located at various points.

A number of safety devices are incorporated in the design of the plant to ensure conformity with statutory regulations and to afford protection to both plant and operator.

Vacuum Industrial Applications Ltd, Wishaw, Lanarkshire, Scotland

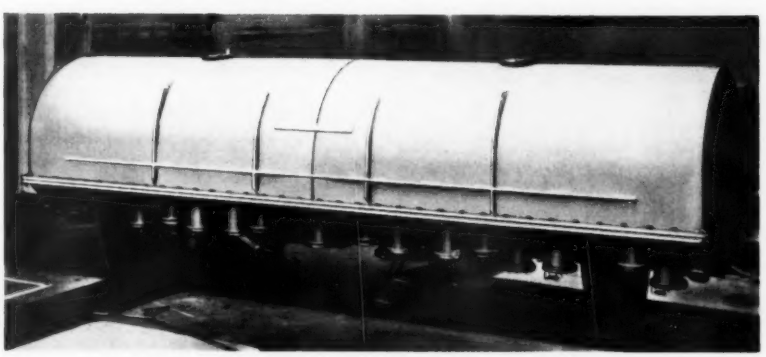
New type MV diffusion pump for CERN's proton accelerator

Metropolitan-Vickers Electrical Co Ltd, Trafford Park, Manchester, 17

The first tank was recently shipped to Geneva for use with the 50MeV proton linear accelerator being constructed by Metropolitan-Vickers for the European Council for Nuclear Research (CERN).

Three such tanks are required, the total volume being some 50,000 litres. They will be continuously evacuated by five mercury diffusion pumps of a type recently developed by M-V, refrigerated baffles being used to prevent the migration of mercury vapour into the tanks. Separate 'rough' pumping systems will be used to obtain the degree of vacuum necessary before the mercury pumps can come into operation.

For shipment, each tank is filled with an inert gas to prevent corrosion during transit and erection.

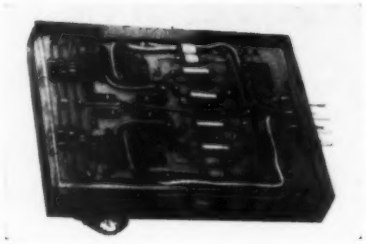


Three of these tanks will be used in the Geneva 50 MeV machine

Potted transistorized counter-scaler from Venner

A transistor decade counter and scaler has been developed by Venner Electronics Ltd to fulfil a demand for a small and compact device having a low consumption which can be used either as a stable divide-by-ten stage or, in conjunction with a meter, as a counting stage. The unit employs transistors and germanium diodes throughout, arranged in four Eccles-Jordan stages with feed back. The device will count or divide from zero up to 30 Kc/s.

It is considerably smaller than equivalent cold cathode counting tubes and their associated circuitry and only requires one power supply of 10 V. The total consumption is 100mW as a scaler and 160mW as a counter. No heating of the stage can occur and therefore it should have a very long life. The stage will prove of great advantage to equipment where space and weight are of importance and where portability is a desirable feature.



Eighty-four components in a space only 4½ by 3¼ inches

The construction is interesting inasmuch as some 86 components, including 8 diodes and 8 transistors, are assembled on a double sided tagboard size 4 by 3 in. This is then encapsulated in epoxy resin to form a block size 4½ by 3¼ by ¾ in., which in turn is fitted with an eight pin plug so that the unit is ready for direct insertion into equipment.

One decade may be directly connected to another, with no additional components, and thus by using four in cascade and fed from a transistorized 10 Kc/s crystal oscillator (also made by Venner) an output pulse every second may be obtained. Alternatively, by connecting a meter to each stage and again feeding the decades from the crystal oscillator but having a switch (or contacts) to interrupt the flow of pulses from the crystal oscillator, a short period timer is obtained which indicates directly on the meters (to the nearest 0·1 millisecond) the time for which the switch (or contacts) have been closed.

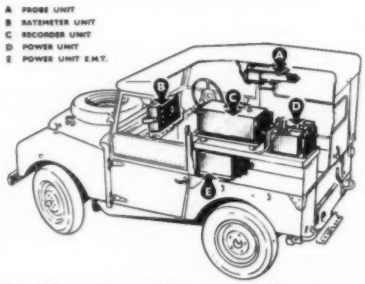
Venner Electronics Ltd, Kingston By-Pass, New Malden, Surrey

Ediswan car-borne gear for prospectors

A highly-sensitive equipment for geological surveys has been designed and developed by The Edison Swan Electric Co Ltd, in conjunction with the AERE, Harwell. It is intended for mounting on a vehicle of the Land-rover type. When in use, the vehicle is driven about until a signal is received. If necessary, either the driver or his passenger can then dismount taking with him the scintillometer probe for manual detection.

The sketch shows the five main items of equipment installed in a vehicle. The scintillometer probe unit will detect a change of ±0·0005% in 0·003% equivalent uranium oxide (U_3O_8) in bedrock. This probe is claimed to have a lower relative background than the geiger-müller-type detectors in which cosmic radiation tends to mask terestrial gamma radiation. The necessary signals are given by the ratemeter unit, which has a single compressed scale and an adjustable threshold alarm which flashes a light and sounds a bell. The time constant of the ratemeter and of the alarm is 1 sec in each case. This ratemeter carries all the operating controls and is designed for mounting within easy reach of the driver or passenger. The recorder is of the inkless type, using *Teledeltos* paper, and moves at 12 in./h with marker facilities for mileage. The time constant of the recorder is 2–5 sec.

The current used for operating this equipment is 3·7 A from a 12 V battery. Stabilization is provided for variations from 11 to 14 V. All valves are of the cold-cathode type, which are largely responsible for the low internal temperature rise of the equipment when in operation. All the units are fully tropicalized, hermetically-sealed and desiccated. Antivibration mountings are used and all interconnecting cables have sealed-type connectors. The separate units are quite small and can be disposed about the vehicle to the best advantage by reason of the 15 ft of interconnecting cables. The probe can be released quickly and, as mentioned before, used as a manual means of detection at close quarters, subject, of course, to the cable limitations.



How the units are disposed in the car

The total weight of the five units with their connectors amounts to 98 lb, made up as follows: probe unit, 14½ by 5 by 5 in., 6 lb; e.h.t. power unit, 11¼ by 9¾ by 9¾ in., 16 lb; ratemeter unit, 14½ by 8½ by 7¼ in. 14 lb; power unit, 10⅜ by 14¼ by 8⅝ in., 21 lb; recorder unit, 19½ by 9¼ by 9⅛ in., 27 lb; and connectors, 14 lb.

The Edison Swan Electric Co Ltd, 155 Charing Cross Rd, London, WC2

Calder penstocks

Control of circulating water to the cooling towers is by Ham, Baker penstocks in the ducts leading to the ponds. Four of these have been installed at Calder A, and a further four are on order for Calder B.

The penstocks are 6 ft wide and 4 ft high, and are made in high grade cast-iron with non-ferrous matching faces. The frame is of heavy one-piece construction; the well-ribbed door is held to a watertight closure by adjustable wedges faced similarly to the frame and is lifted by a heavy-section rising spindle, which is of high-tensile manganese bronze to avoid the possibility of corrosion.

The hand-operated, machine-cut bevel reduction gear is easily operated by one man, the weight of the door being carried on heavy ball thrust bearings. As there is no appreciable head of water, two-speed gear is not required.

The gear box is supported on a pillar, carried on cross channels spanning the extended side members of the guide frame, the whole thus forming a self-contained unit. This ensures perfect alignment of the spindle which is essential if friction is to be minimized.

Sludge which inevitably collects in the system can be sluiced out by means of four 12 in. disc valves, and two 12 in. flat outlet valves in the culverts and ponds. A number of smaller flat outlet valves control the warm water required for de-icing purposes.

Ham, Baker & Co Ltd, Langley Green, Oldbury, Birmingham

10,000 cycles on Molytox

In the BNEC Calder Hall symposium paper by Ghalib and Bowen it is reported that during the development period no suitable hydrocarbon oils could be found to withstand the radiation inside the reactor vessel. Consequently, for lubrication of the control rod drives it was decided after tests at high temperatures in CO_2 to use molybdenum disulphide (MoS_2) dry lubricant. Results showed that untreated surfaces of hard shaft steel seized after 10 cycles, but if initially brushed with a suspension of MoS_2 the coefficient of friction dropped from 0·25 to 0·1 and after 10,000 cycles of operation the parts were still in good condition. Rolling friction was investigated using a special rig and it was found that bearings with steel cages, hard-coated with MoS_2 and then given an additional dipping were the best. They achieved 3 by 10^6 rev satisfactorily.

The molybdenum disulphide preparation used is known as *Molytox* and is manufactured by Rocol Ltd.

Not only does it lubricate; it protects the control mechanisms from corrosion by carbon dioxide, heat and humidity. For this reason *Molytox* is also being used for the pre-treatment of control equipment to be held for replacements and spares.

For equipment which is used only in an emergency and for components which may have to be exposed to abnormal conditions of moisture and corrosion, a 'reactor fluid' based on a silicone varnish containing molybdenum disulphide has been developed. In principle it is identical with *Molytox* but the presence of a water repellent silicone gives it added protective capacity.

PROPERTIES OF MOLYBDENUM DISULPHIDE

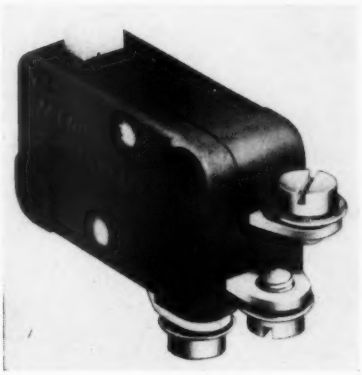
Chemical formulae	MoS_2
Appearance	Blue grey/black lustrous solid or powder
Hardness	1 to 1·5 (Moh's scale)
Density	4·80
Crystal form	Hexagonal or trigonal plates
Cleavage	Perfect basal yields thin laminae
Coefficient of friction	0·04
Maximum normal working pressure	100,000 lbs/in^2
Electrical resistance	High at low potential but drops as potential rises
Reaction on heating	Melts 1185°C (2165°F) Sublimes 450°C (842°F) Decomposes in vacuo 982°C (1800°F) Decomposes in nitrogen 1427°C (2600°F)
Reaction at low temperature	No action
Reaction in oxygen	Begins at 399°C (750°F)
Reaction in gases	Inert except in fluorine and on heating in chlorine. Reduced in hydrogen
Reaction in solvents	Inert
Reaction in water	Inert
Reaction in acids	Inert except in aqua regia, hot concentrated sulphuric acid and hot nitric acid

There are only two existing official standards for the use of molybdenum disulphide for lubricating purposes. These are specification MIL-L-7866 (Aer) issued by the United States Bureau of Aeronautics, Department of the Navy, and specification CS. 2819 issued by the Ministry of Supply. These are accepted as minimum requirements in all Rocol uses of molybdenum disulphide. In fact, *Rocol* molybdenum disulphide far exceeds the requirements of these specifications for particle size.

Rocol Ltd, Rocol House, Swillington, Leeds

Ibex House, Minories, London, EC3

Micro-Switchette now with nylon plunger



New plunger is self lubricating, so switch is more rugged

An improved version of the well-known Burgess 'V3' Micro Switchette is now available. The price is unaltered at 4s. 6d., less quantity discount.

Made to the same general specification and dimensions as the present model, with which it is interchangeable, the improved 'V3' has a nylon plunger in place of the phenolic resin plunger used formerly.

Nylon offers important advantages over other moulding materials for plungers. Life expectation is greater because, being self-lubricating, nylon reduces plunger-to-case friction. Foreign bodies can embed themselves in the plunger rather than jam it or 'seep' past it into the switch mechanism. The Switchette as a whole will withstand rougher treatment since the elasticity of the nylon plunger can absorb shock without distortion or abrasion.

Burgess Product Co Ltd, 127 Victoria Street, London, SW1

Solid, liquid scintillators in great variety

The versatility of liquid scintillation detectors provides an excellent means for approaching many problems in the detection of nuclear radiation. In recognition of the diversity of counting applications that are encountered, Nuclear Enterprises (GB) Ltd are now providing what is claimed to be the greatest variety of liquid scintillators ever offered.

These include boron-, cadmium- and gadolinium-loaded scintillators for neutron detection, lead-loaded detectors for enhanced gamma ray response and a scintillating gel for the counting of suspended materials.

In addition, the firm is offering several types of unloaded liquid and plastic scintillators of high efficiency. The plastic phosphor NE 101 is now available in many new forms. Thin sheets down to 2 mils possessing low gamma ray background for alpha- and beta-counting and suitable for X-ray intensification or gamma radiography are available. In addition, small perfect spheres from 0·1 to 1 mm diameter and scintillating powder uniformly 1 micron diameter are available. At the other extreme, large single optical blocks up to 200 kg can be supplied for ultrasensitive detectors (such as body counters or cosmic ray detectors). The plastic can be machined to almost any shape for specific research needs. Most of these products are completely new, and Nuclear Enterprises will be pleased to co-operate with research workers in developing new applications.

Nuclear Enterprises (GB) Ltd, Bankhead Medway, Sighthill, Edinburgh

Last month NUCLEAR POWER visited the works and research centre of Babcock and Wilcox Ltd at Renfrew near Glasgow. Here, the firm is rapidly equipping itself to undertake heavy nuclear engineering work of all kinds.

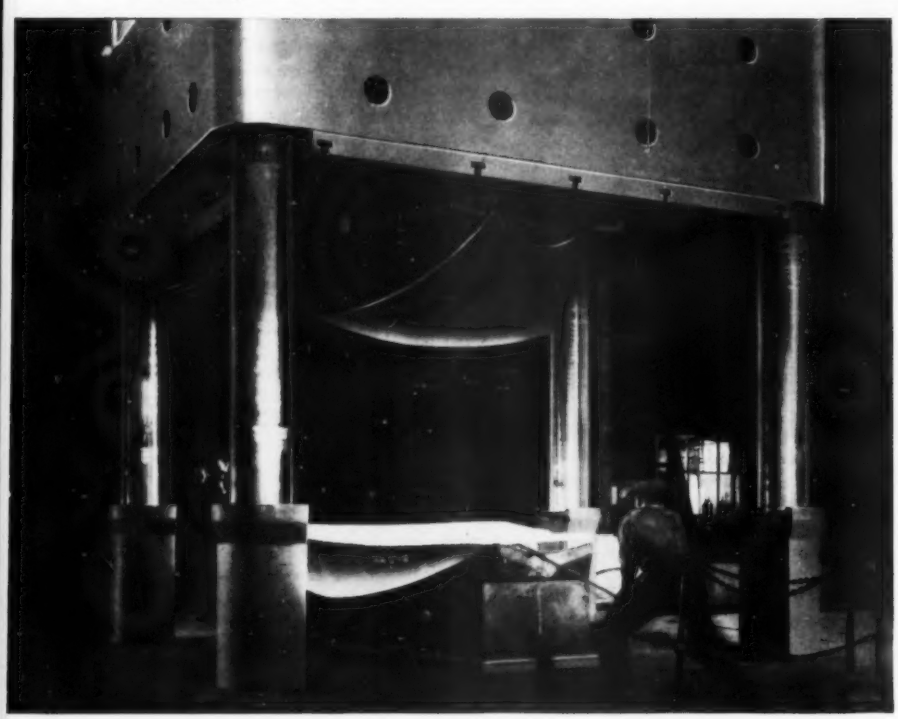
Research and Production on Clydeside

the Babcock and Wilcox works

THE HUGE PRODUCTIVE CAPACITY of Babcock and Wilcox's Renfrew works is increasingly being applied to nuclear power projects and although much of it is still engaged on the firm's extensive business in high-pressure water-tube, land, marine, and packaged boilers its large new tube and manifold shops, built at a cost of over £700,000 have been planned very much with heat exchangers and other major items of nuclear power stations in mind. The company say that as we approach the stage when all new power station plant installed in Great Britain will be nuclear, the design and manufacture of such plant will become a major factor in their output.

Babcock's are concerned not only with developments in the field of heat-exchangers or steam-raising plant but are also rapidly equipping themselves to undertake the design and construction of reactors. This involves many aspects of large pressure vessel construction, the design and development of fuel elements and their handling equipment. As is well known, Babcock and Wilcox Ltd are associated with the English Electric Co Ltd and Taylor Woodrow Ltd in the design and construction of gas-cooled graphite-moderated power stations for the CEA, but it is understood that the members of the group are free to act independently on other types of reactor.

Domed heat exchanger shell heads for Chapel Cross are assembled on jigs from eight segment plates



The segment plates are formed hot in a 2,000-ton press. The hydraulic cylinders are all below floor level in a 40 ft deep shaft

For the furtherance of these plans, Babcock and Wilcox recently set up an Atomic Energy Department with T. B. Webb as Manager, under W. F. C. Schaap (Director and Chief Engineer of the company). Assistant Manager is W. R. Wootton, and Dr W. B. Carlson is in charge of research.

The Babcock and Wilcox patented water-tube boiler was first introduced into Europe in 1881 and the British company was formed in Glasgow in 1891. In 1896 the present Renfrew works were started and from 10 acres it has now grown to 165. The present Director at Renfrew is Mr C. H. Davy and the General Works Manager is Mr Douglas D. Cruickshank.

At the moment, the main feature of interest at Renfrew from a nuclear energy point of view is the production of heat exchangers for the AEA's nuclear power plant at Chapel Cross, Annan. These are identical to those supplied for Calder Hall A and B stations and have been fully described in recent issues of NUCLEAR POWER. Production of the 17 ft 6 in. dia, 80 ft high boilers is on a limited mass production basis and the six cylindrical sections and two domed ends which comprise the shells are sent separately by road to the site.

This production is done in the drum shop and the components are made from *Coltuf 28* steel plate (UTS, 28-32 t/in^2; yield, 17 t/in^2)—1$\frac{5}{16}$ in. thick for the sides, 1$\frac{3}{4}$ in. for the domes. The plate is examined on delivery for laminations, using ultrasonic methods developed by the firm. The cylindrical sections are cold-rolled in halves and then welded together. Thermal sleeve holes are then drilled and the sleeves welded into position. These welds are all tested by halogen leak-detecting apparatus. The sections are braced internally for transport and stress-relieved in a large gas-fired oven before despatch.

The end domes are formed in eight petal sections, these being pressed hot in a 2,000-ton press. This press is capable of accurately forming pressings in plate up to 7 in. thick. The sections together with entry and exit flanges, are welded together on special jigs. Throughout, extensive use is made of both ultrasonic and X-ray testing. In a special department is located a 2MV X-ray machine which is one of the two most powerful in Europe. It is used for inspecting seam welds in very thick pressure vessels and requires only about 15 minutes exposure for 6 in. plate. It will be recalled that Babcock's pioneered the process of machine fusion welding of pressure vessels some 25 years ago and this technique has been brought to the stage where absolutely no riveting whatever is done in the works. Thicker pressure vessels such as h.p. steam drums are hot-rolled in an 8000-ton machine.

The stud-tube heat exchanger elements for the Calder type reactors are made in the tube and manifold shops and the elliptical studs are flash welded to the tubes in a battery of semi-automatic machines developed for the purpose. This tubing is bent cold after studding, there being no studs on the actual bend. For future plants, close bending to a much smaller radius might be required and marine superheater elements of very similar design are already being bent hot at Renfrew. Before despatch, these elements are given a hydrogen leak test. In the first Calder contract, no leaks were ever found so now the test is confined to a proportion of the elements.

Using electric strain gauges, a push-out in a heavy pressure shell is tested both inside and out

A development of great interest from the nuclear point of view is the use of extruded push-outs on very thick shells. The shell is originally overthick in the region of the push-out and when the edge is prepared, a first class weld to the pipe branch can be made.

The Research station is situated some distance from the works on the way to Glasgow. There, a staff of some 270 are equipped with modern and extensive equipment for chemical and physical testing, mechanical testing, metallurgical examination and application of electronics to engineering.

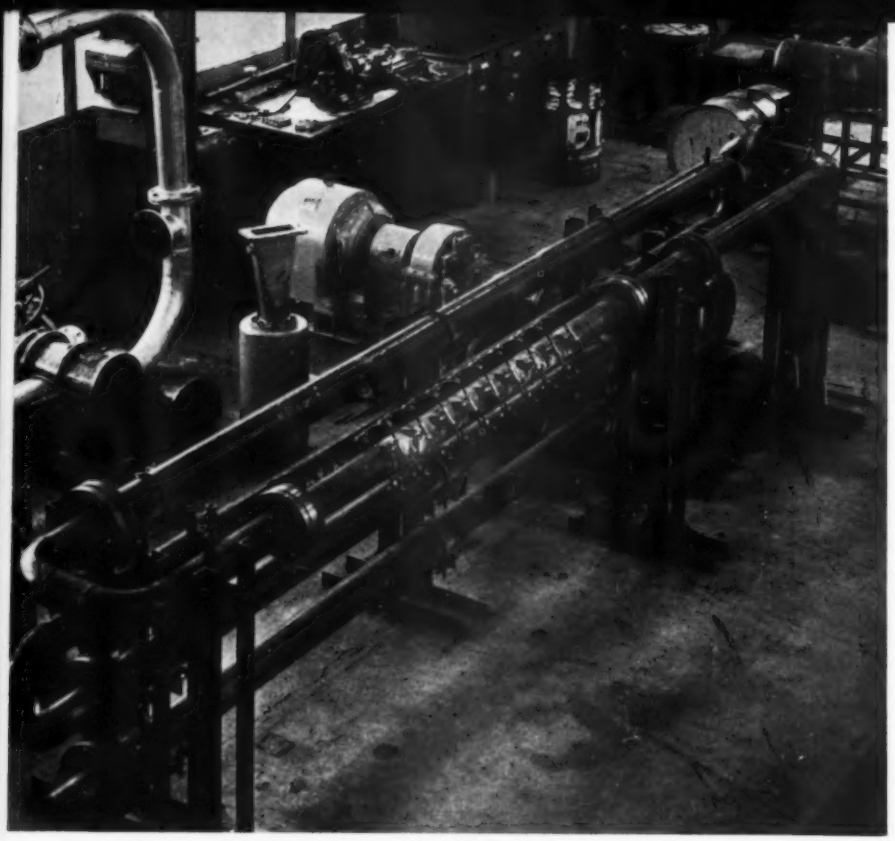
Nuclear research at Renfrew is predominantly, though not exclusively, directed to problems of heat exchange both from fuel to coolant and from coolant to steam. Other investigations receiving high priority are the development of large pressure vessels for pressurized water reactors (the NPD contract —see this issue, Worldview) and mechanisms for fuel charging and discharging.

In the chemistry department, fuel can compatability tests are being carried out. Magnox and zirconium alloys and other possible canning materials are at present being tested in CO_2 at up to 450°C and the experiments are shortly to be extended to include the effects of dynamic conditions. It is also intended to extend these to liquid-metal compatability studies. New equipment will incude additional spectrographic apparatus.

Thermal cycling tests on magnox-canned uranium rods are in progress using a specially designed rig. The specimens are enclosed in a steel tube filled with argon and cyclically lowered into and removed from an electrically heated chamber maintained at about 400°C. Ratcheting is observed by X-ray.

Considerable effort is being applied to the design of large pressure vessels for very high pressures and apart from problems of mechanical design of closures and sealings, this includes investigations into the brittle fracture of special alloy

One of a battery of 84, this hot stress rupture machine is used to test the performance of canning materials under high temperature conditions



Nearing completion, this test rig will measure heat transfer and pressure loss of proposed fuel cans in various coolant gases

steels and creep properties of steel and light non-ferrous alloys. A battery of 84 hot-stress-rupturing machines is available and a number of these are at present working on canning materials. More of these machines are shortly to be housed in a new extension to the laboratories and, in addition, 24 creep testing machines are to be installed. This extension will greatly facilitate tests on alloys of aluminium, beryllium and zirconium.

For fatigue testing of complete pressure vessels, a Werner and Pfleiderer pulsating pressure plant capable of 4,500 lb/in.^{2} has been in use since 1952 and additional hydraulic plant with a capacity of 6,000 lb/in.^{2} is to be installed shortly.

In the heat exchanger department, work is divided into two main sections: heat exchanger elements; fuel elements. For the former, the testing consists of a vertical flue through which hot air from an oil-fired combustion chamber is passed by a forced-draught fan. In the flue, test-assemblies of extended-surface elements are placed and supplied with cooling water in a manner simulating nuclear heat-exchange conditions. Measurements are made of heat transfer and draught loss. A more advanced rig using a closed gas circuit at elevated pressure is at present being designed and when installed, will permit extension of these tests to considerably higher ratings.

To speed up selection of suitable can fin systems, a 'quick-sorting' system is used. In this way, the more obvious failures can be quickly eliminated, thus freeing effort for work on the more promising ones. In this rig, the elements are mounted in a lagged vertical cylindrical pipe through which air is blown. The elements—which are often in brass to save time and expense of making real ones—are steam-heated and quick results of heat transfer and head loss are quickly obtained. Heat releases of up to 8 kW/ft can be obtained in this rig.

For further tests, a new closed-circuit rig has just been completed. In this, the test channel is horizontal and any gas may be used as the coolant. The elements are electrically heated and two main methods are being investigated. In the first, the heater element consists of an internal tube cut into the form of a spiral. This is insulated from the fuel can by anodizing the inside of the can—this provides electrical insulation between heater and can but no thermal insulation. The other method uses a solid rod cut with longitudinal slots along which conductors are laid. Heat releases of up to 15 kW/ft are obtainable by these means.

An interesting specific piece of work being undertaken is the design of a pressurized water loop for the Harwell DIDO reactor. In order to solve the complex three-dimensional problems of piping layout in a confined space a model has been constructed in which most of the components are transparent plastic. This can be easily softened by heat and then reset, so that alterations in piping runs can be quickly investigated and finalized before drawing office work begins.

Over 300 types of finned cans have already been tested—here are just a few

Reactor Physics-7

James F. Hill Senior Lecturer, Reactor School, Harwell

How are neutrons used up and how is the critical size of a bare reactor found? these questions are answered in NUCLEAR POWER's basic course this month

1. Neutron leakage—continued

In the design of a reactor it is clearly necessary to conserve neutrons, so that any loss of neutrons must be reduced to a minimum. It is therefore of interest to consider the leakage of neutrons as a function of the buckling, which, as has been said, for a critical reactor depends on the dimensions of the system. Now it will be seen later that, in fact, the buckling is proportional to the inverse square dimensions of a system. Thus the larger the system the smaller the buckling and vice versa.

From 6.33 it is seen that the fraction of slowing down neutrons leaking from the system is

$$1 - e^{-B^2 L_s^2} \tag{7.1}$$

and from 6.37 it is seen that the fraction of thermal neutrons leaking from the system is

$$\frac{B^2L^2}{1+B^2L^2} \tag{7.2}$$

Now both of these expressions decrease as B^2 is decreased, that is the leakages decrease as B^2 is decreased and so from the remarks above the leakages decrease as the size of the system increases.

2. The multiplication cycle in a finite system

We are now in a position to consider the fate of neutrons in a finite multiplying medium. Let

α = fraction of slowing-down neutrons remaining in the system (7.3)

β = fraction of thermal neutrons remaining in the system (7.4)

Then, starting with one fission neutron we have the chain given in Figure 7.1.

This cycle has been written in general terms for the leakage factors α and β. However, in the case of the bare reactor, we have seen (see (6.32) and (6.37)) that

$$\alpha = e^{-B^2 L_s^2} \tag{7.5}$$

and

$$\beta = \frac{1}{1+B^2L^2} \tag{7.6}$$

Then the critical condition

$$\alpha\,\beta\,k = 1 \tag{7.7}$$

yields

$$\frac{ke^{-B^2 L_s^2}}{1+B^2L^2} = 1 \tag{7.8}$$

as previously deduced in (6.38).

It is instructive to consider the chain in Figure 7.1 as a balance sheet for the neutrons in a reactor. Then from it the number of neutrons available for any particular process can be found.

Suppose now the fuel is a mixture of U^{235} and U^{238}. Then each neutron absorbed in U^{235} produces $\eta\,(25)$ fission neutrons and $\varepsilon\eta\,(25)$ fast neutrons. These $\varepsilon\eta\,(25)$ fast neutrons are available to carry on the sequence shown in Fig. 7.1. However, one neutron must be finally left to carry on the chain reaction so the number of neutrons available for all other processes (resonance capture, thermal capture, leakage, etc.) must be

$$\varepsilon\eta\,(25) - 1 \tag{7.9}$$

Then per neutron absorbed in U^{235} the $\varepsilon\eta\,(25)$ neutrons can be divided up as :—

neutrons absorbed in U^{235}	$= 1$
neutrons absorbed in U^{238}	$= C$
neutrons absorbed in materials other than fuel	$= A$
neutrons escaping from the system	$= E$

so that

$$\varepsilon\eta\,(25) - 1 = C+A+E \tag{7.10}$$

3. The conversion factor

The quantity C defined above is called the conversion factor because each neutron absorbed in U^{238}, whether as a slowing-down or thermal neutron, leads eventually to the production of one Pu^{239} atom, and so C represents the number of Pu^{239} atoms produced per atom of U^{235} destroyed. As Pu^{239} is an alternative fissionable material to U^{235} then C is clearly an important quantity in a reactor.

Pu^{239} is produced from U^{238} by the sequence of reactions

$$U^{238} + n \longrightarrow U^{239} \xrightarrow{23{\cdot}5m} N^{239} \xrightarrow{2{\cdot}33d} Pu^{239} \tag{7.11}$$

C can readily be found from Fig. 7.1. This scheme is in terms of one fission neutron, so to convert to one neutron absorbed in U^{235} all quantities in Fig. 7.1 must be multiplied by $\eta\,(25)$.

Then the neutrons captured in resonances in U^{238} per neutrons absorbed in U^{235} is

$$\eta\,(25)\;\alpha\varepsilon\,(1-p) \tag{7.12}$$

Now also from Fig. 7.1

$$\eta\,(25)\;\alpha\beta\varepsilon pf \tag{7.13}$$

thermal neutrons are captured in the fuel, and so

$$\eta\,(25)\;\alpha\beta\varepsilon pf\,\Sigma_a\,(28)/\Sigma_a\,(\mathrm{U}) \tag{7.14}$$

thermal neutrons are captured in the U^{238} where $\Sigma_a\,(28)$ and $\Sigma_a\,(\mathrm{U})$ are respectively the cross sections per cm^3 of U^{238} and the fuel. Then combining (5.31), (5.33) and (5.34)

$$\eta\,(\mathrm{U}) = \eta = \eta\,(25)\;\Sigma_a\,(25)/\Sigma_a\,(\mathrm{U}) \tag{7.15}$$

so that (7.14) becomes on using (7.15)

$$\alpha\beta\,\eta\varepsilon pf\,\Sigma_a\,(28)/\Sigma_a\,(25) \tag{7.16}$$

$$= \alpha\beta k\;\Sigma_a\,(28)/\Sigma_a\,(25) \tag{7.17}$$

$$= \Sigma_a\,(28)/\Sigma_a\,(25) \text{ if the system is critical} \tag{7.18}$$

Thus C is given by the sum of (7.18) and (7.12), so

$$C = \Sigma_a\,(28)/\Sigma_a\,(25) + \alpha\,\eta\,(25)\;\varepsilon\,(1-p) \tag{7.19}$$

Because α depends on the leakage of slowing-down neutrons and also on the particular model adopted for the

THE FATE OF NEUTRONS in a finite multiplying medium is considered and a neutron balance is obtained. An important item is the conversion factor C representing the number of plutonium atoms created from uranium-238 per atom of U-235 destroyed. For a typical graphite moderated, natural uranium reactor the value of C is shown to be about 0.766.

The critical size of a bare reactor is derived in terms of Bessel functions and the expression indicates that for a given value of the buckling there are an infinite number of possible values of the extrapolated height and radius of the critical cylinder. There are however minimum values of these parameters, at which the other becomes infinite.

ON CONSIDERE le sort des neutrons dans un milieu multipliant infini et l'on obtient un bilan de neutrons. Très important est le facteur de conversion C, qui représente le nombre d'atomes de plutonium obtenus d'uranium-238 par atome U-235 détruit. On démontre que pour un réacteur typique à l'uranium naturel et modéré au graphite la valeur de C est environ 0,766.

Les dimensions critiques d'un réacteur sans réflecteur sont exprimées en fonctions de Bessel; l'expression obtenue indique que, pour une valeur donnée du Laplacien du réacteur, il y a un nombre infini de valeurs possibles de l'hauteur et rayon extrapolés pour le cylindre critique. Néanmoins, chacun de deux paramètres a une valeur minimum, pour laquelle l'autre paramètre devient infiniment grand.

DAS SCHICKSAL der Neutronen in einem endlichen vermehrenden Medium wird betrachtet und es wird eine Neutronenbilanz erhalten. Wichtig ist der Konversionsfaktor C, welcher die Zahl der vom Uran-238 erzeugten Plutoniumatome per jedes zerstörte U-238-Atom darstellt. Es wird gezeigt, dass für einen typischen graphitmoderierten Natururan-Reaktor der C-Wert etwa gleich 0,766 ist.

Die kritische Grösse eines reflektorlosen Reaktors wird in der Gestalt von Besselfunktionen dargestellt; der erhaltene Ausdruck bedeutet, dass es für einen gegebenen Flusswölbungswert unendlich viele mögliche Werte der extrapolierten Höhe und Halbmesser des kritischen Zylinders gibt. Jedes dieser Parameter hat jedoch einen Kleinstwert, für welchen das andere Parameter unendlich gross wird.

EN ESTE ARTICULO se examina el destino de los neutrones en un medio multiplicador finito y se obtiene un equilibrio de neutrones. Un importante elemento es el factor de conversión C, que representa el número de atomos de plutonio creados del uranio-238 por cada atomo de U-235 destruido. Para un reactor tipico de uranio natural, moderado con grafito, el valor de C es indicado en alrededor de 0,766.

El tamaño critico de un reactor descubierto es derivado a base de las funciones de Bessel y la expresión revela que para un valor determinado del "buckling" existe un número infinito de posibles valores de la altura y radio extrapolados del cilindro critico. Hay, sin embargo, valores mínimos de estos parámetros, a los cuales el otro se convierte en infinito.

РАССМАТРИВАЕТСЯ участь нейтронов в конечной размно-жающей среде и выводится баланс нейтронов. Важным является коэффициент конверсии C, изображающий число атомов плутония, получаемых из урана-238 на каждый уничтоженный атом U-235. Указывается, что для типичного реактора с природным ураном и графитовым замедлителем значение C равно примерно 0.76·6

Критические размеры реактора без отражателя выводятся в форме бесселевских функций; полученное выражение указывает, что для данного значения параметра кривизны существует бесконечно много возможных значений экстраполированной вышины и радиуса критического цилиндра. Однако каждый из этих параметров имеет минимум, для которого значение другого параметра становится бесконечно большим.

Erratum

An error occurs in the first column of the last instalment of this series (p 307). The value 10.2 barns in the second line after equation (6.9) should read 290 barns: in equation (6.10) the figure should be 10.2 barns and not 290 barns.

behaviour of the neutrons it is often put equal to unity (thus making the conversion factor apply to the infinite system) and C written

$$C = \Sigma_a(28)/\Sigma_a(25) + \eta(25)\,\varepsilon(1-p) \qquad (7.20)$$

For natural uranium this reduces to

$$C = 0{\cdot}552 + 2{\cdot}08\,\varepsilon\,(1-p) \qquad (7.21)$$

In a typical graphite natural uranium reactor with, say, $\varepsilon = 1{\cdot}03$ and $p = 0{\cdot}9$ then

$$C = 0{\cdot}766 \qquad (7.22)$$

so that each U^{235} atom destroyed about 0·77 atoms of Pu^{239} are produced, and of these 0·55 are from thermal capture and 0·22 from resonance capture. Thus about two and a half times as many Pu^{239} atoms are produced by thermal capture as by resonance capture.

4. The neutrons captured wastefully

Neutrons which are not absorbed in the fuel are generally wasted and the quantity A is the number of thermal neutrons absorbed in materials other than the fuel per neutron absorbed in U^{235}. From Fig. 7.1 (again multiplying by η (25))

$$A = \eta(25)\,\alpha\varepsilon p\beta\,(1-f) \qquad (7.23)$$

$$= \frac{\eta(25)}{\eta(U)}\left(\frac{1}{f} - 1\right) \qquad (7.24)$$

It is to be noted that this does not depend on the leakage factors α and β as it simply represents a straight competition for the neutrons by the non-fuel and the U^{235}.

For natural uranium this reduces to

$$A = 1{\cdot}41\left(\frac{1}{f} - 1\right) \qquad (7.25)$$

5. The neutrons escaping

Both slowing-down and diffusing neutrons escape from the reactor, and adding the two appropriate terms together in Fig. 7.1 gives

$$E = \eta(25)\,(1-\alpha)\varepsilon + \eta(25)\,\alpha\varepsilon p\,(1-\beta)$$
$$= \varepsilon\,\eta\,(25)\{(1-\alpha) + \alpha p\,(1-\beta)\} \qquad (7.26)$$

This, of course, is a function of α and β and is zero for $\alpha = \beta = 1$, that is, an infinite system.

6. The neutron balance

Consider now (7.10). This shows that for a set of systems, containing U^{235} as the fissionable material, in which the fast fission factor ε remains constant, the left-hand side of the equation remains constant and hence the right-hand side remains constant. (As ε in general depends on the geometry of the fuel element only, then the condition ε constant is satisfied by systems using the same fuel elements.)

Now if the sum of C, A and E remains constant it means that a change in any one of them means a compensating change in either or both of the others. For example, if we consider a particular lattice of fuel elements and moderator in a reactor and then use the same fuel elements in a different lattice, the number of neutrons, for example, going to convert U^{238} into Pu^{239} will in general be different in the two cases. Also, so will the numbers captured wastefully and escaping, but, the sum of these three neutron fates must be the same. Thus we are at liberty to choose where the neutrons go, that is, into C, A, or E, but with the over-riding consideration that the sum of these is fixed.

Now let us consider the conversion factor C. This can be seen from (7.19) to consist of two terms. The first term depends only on the constants of the uranium and the value of this term is largest for natural uranium because it has the smallest fraction of U^{235}. As the fraction of U^{235} is increased (that is the uranium is enriched) this term will decrease, and going to say twice-enriched uranium will approximately halve this term, from 0·552 to 0·27. Thus using enriched uranium will produce a marked decrease in the conversion factor unless the second term in (7.19) can be increased by way of compensation.

The quantity A will also vary with the uranium enrichment, and in a particular lattice if the only change is to substitute enriched for natural uranium, then A will decrease. This is because η (U) increases with enrichment and for the same lattice the fraction of neutrons absorbed by the fuel will increase so that $f^{-1}-1$ will decrease.

The variation in E is not simple and can only be determined by calculation for a particular system. In general, however, it would be expected to increase with increasing enrichment, because increased enrichment means a larger value of k and hence also the buckling and as has been seen the neutron leakage increases with increasing buckling.

7. The critical size of a bare reactor

It has been seen (equation (6.26)) that the thermal neutron flux ϕ in a bare reactor is given by the equation

$$\nabla^2\phi + B^2\phi = 0 \qquad (7.27)$$

with

$$k = e^{B^2 L_s^2}(1 + B^2 L^2) \qquad (7.28)$$

if the reactor is to be critical.

If $B^2L_s^2$ is small (7.28) can be written approximately as

$$k \simeq (1 + B^2L_s^2)(1 + B^2L^2) \qquad (7.29)$$

and if B^2L^2 is also small this can be further approximated to by

$$k \simeq 1 + B^2(L^2 + L_s^2) = 1 + B^2M^2 \qquad (7.30)$$

where

$$M^2 = L^2 + L_s^2 \qquad (7.31)$$

M being called the migration length.

From (7.30) then

$$B^2 \simeq (k-1)/M^2 \qquad (7.32)$$

so (7.27) then becomes

$$\nabla^2\phi + \left(\frac{k-1}{M^2}\right)\phi = 0 \qquad (7.33)$$

Consider now the solution of (7.27) for the case of a cylinder, with symmetry about the axis. The co-ordinates are as shown in Fig. 7.2.

The radius of the cylinder is R and the height H.

The equation to be solved is then

$$\frac{\partial^2\phi}{\partial r^2} + \frac{1}{r}\frac{\partial\phi}{\partial r} + \frac{\partial^2\phi}{\partial z^2} + B^2\phi = 0 \qquad (7.34)$$

Suppose $\phi = P(r)\,Z(z)$ (7·35)

where P is a function of r only and Z is a function of z only. Then substitution of (7.35) into (7.34) leads to

$$\frac{1}{P}\frac{d^2P}{dr^2} + \frac{1}{rP}\frac{dP}{dr} + \frac{1}{Z}\frac{d^2Z}{dz^2} + B^2 = 0 \qquad (7.36)$$

The first two terms are functions of r only and the third of z only, so for (7.36) to be satisfied for all values of r and z the sum of the first two terms must be a constant and the third term must be a constant. So let

$$\frac{1}{Z}\frac{d^2Z}{dz^2} = -\beta^2 \qquad (7.37)$$

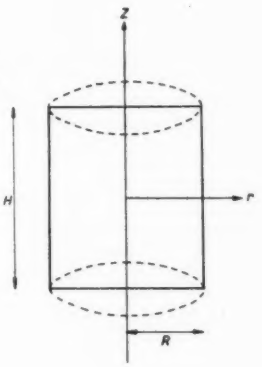


Fig 7.2 ***cylindrical coordinates***

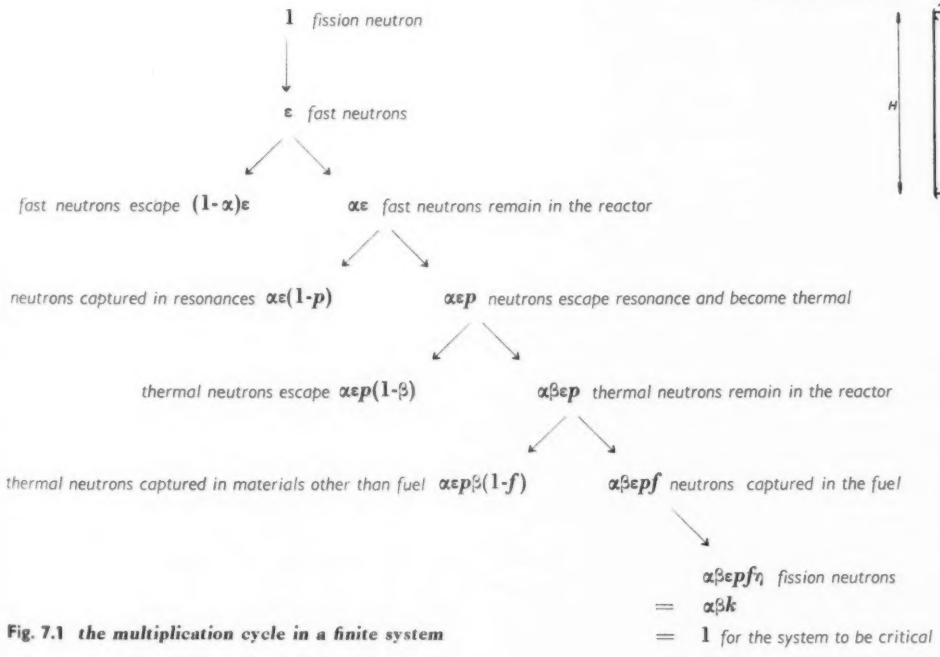

1 fission neutron
ε fast neutrons
fast neutrons escape (1-α)ε
αε fast neutrons remain in the reactor
neutrons captured in resonances αε(1-p)
αεp neutrons escape resonance and become thermal
thermal neutrons escape αεp(1-β)
αβεp thermal neutrons remain in the reactor
thermal neutrons captured in materials other than fuel αεpβ(1-f)
αβεpf neutrons captured in the fuel
αβεpfη fission neutrons
= αβk
= 1 for the system to be critical

Fig. 7.1 ***the multiplication cycle in a finite system***

which gives

$$Z(z) = A \cos \beta z + C \sin \beta z \tag{7.38}$$

where A and C are arbitrary constants.

Now physically $Z(z)$ must be a symmetrical function about $z = 0$ so the sine term is inadmissible. This means that C must be zero, so

$$Z(z) = A \cos \beta z \tag{7.39}$$

Also $Z(z)$ must satisfy the required boundary condition at the ends of the cylinder. This is done by making ϕ zero, that is also Z zero at the extrapolated distance (see equation 3.5). The extrapolated distance is

$$\frac{1}{2} H_e = \frac{1}{2} H + 0.71 \lambda_t \tag{7.40}$$

where λ_t refers to the reactor core, so

$$Z\left(\frac{H_e}{2}\right) = A \cos \beta \frac{H_e}{2} = 0 \tag{7.41}$$

and for this to be satisfied

$$\beta H_e/2 = \pi/2 \tag{7.42}$$

or

$$\beta = \pi/H_e \tag{7.43}$$

Now substituting from (7.37) into (7.36)

$$\frac{1}{P} \frac{d^2P}{dr^2} + \frac{1}{rP} \frac{dP}{dr} + (B^2 - \beta^2) = 0 \tag{7.44}$$

and putting

$$\left.\begin{aligned} B^2 - \beta^2 &= \alpha^2 \\ \alpha r &= x \end{aligned}\right\} \tag{7.45}$$

(7.44) becomes

$$x^2 \frac{d^2P}{dx^2} + \frac{x dP}{dx} + x^2 P = 0 \tag{7.46}$$

and this is Bessel's equation of order zero.

Thus

$$P(r) = DJ_0(x) + EY_0(x) \tag{7.47}$$

or

$$P(r) = DJ_0(\alpha r) + EY_0(\alpha r) \tag{7.48}$$

Where D and E are arbitrary constants.

Now $P(r)$ must remain finite at $r = 0$ so this means E must be zero, and

$$P(r) = D J_0(\alpha r) \tag{7.49}$$

and using the same arguments as before

$$\phi(R_e) = 0 \qquad R_e = R + 0{\cdot}71 \lambda_t \tag{7.50}$$

so that

$$P(R_e) = 0 = D J_0(\alpha R_e) \tag{7.51}$$

$$\therefore \alpha R_e = 2{\cdot}405 \ldots \tag{7.52}$$

$$\therefore \alpha = 2{\cdot}405 / R_e \tag{7.53}$$

So combining (7.39) and (7.49) the thermal neutron flux distribution is given as a function of r and z by

$$\phi = A' J_0(\alpha r) \cos \beta z \tag{7.54}$$

where $A' = AD$ is an arbitrary constant, and

$$B^2 = \alpha^2 + \beta^2 = \left(\frac{2.405}{R_e}\right)^2 + \left(\frac{\pi}{H_e}\right)^2 \tag{7.55}$$

The reason there is an arbitrary multiplying constant in (7.54) is that this constant will be determined by the power level in the reactor and so cannot be specified by the analysis given here which is unrelated to the power.

The important conclusion to be seen from the above discussion is that the buckling and the extrapolated height and radius of the critical cylinder are related by (7.55). In other words any two of these quantities can be chosen and the third found from (7.55). Thus for a given value of the buckling, and this means the same lattice arrangement, there is an infinite number of possible values of R_e and H_e.

There is, however, a restriction on the acceptable values of R_e and H_e because of (7.55). There is a minimum radius given by

$$(R_e)_{min} = 2{\cdot}405 / B \tag{7.56}$$

obtained when H becomes infinite and similarly a minimum height

$$(H_e)_{min} = \pi / B \tag{7.57}$$

when R becomes infinite.

An alternative way of looking at the problem is to say that, subject to (7.56) and (7.57) a value of R and H can be chosen and from (7.55) the required value of B^2 is found. This then means that to make the reactor critical a lattice with this value of B^2 must be used.

When considering the problem of heat removal from a reactor it is important to know the value of the maximum flux to the average flux as this is the same as the maximum to average heat production. In the case of the cylindrical reactor these are quoted for the radial and axial directions separately as

$$\alpha_R^{-1} = \int_0^R \phi \, 2\pi r dr \Big/ \phi_{max} \int_0^R 2\pi r dr \tag{7.58}$$

which from (7.54), as $\phi_{max} = A'$ gives

$$\alpha_R = \frac{\alpha R}{2 J_1(\alpha R)} \tag{7.59}$$

and

$$\alpha_Z^{-1} = \int_0^{\frac{H}{2}} \phi \, dz \Big/ \phi_{max} \int_0^{\frac{H}{2}} dz \tag{7.60}$$

and from (7.54) this gives

$$\alpha_Z = \frac{\beta H}{2} \operatorname{cosec} \frac{\beta H}{2} \tag{7.61}$$

If we suppose $R \simeq R_e$, $H \simeq H_e$, then

$$\alpha = 2{\cdot}405/R, \qquad \beta = \pi/H \tag{7.62}$$

and substituted into (7.59) and (7.61) these give respectively

$$\alpha_R = 2{\cdot}405/2 \times 0{\cdot}5191 = 2{\cdot}316 \tag{7.63}$$

and

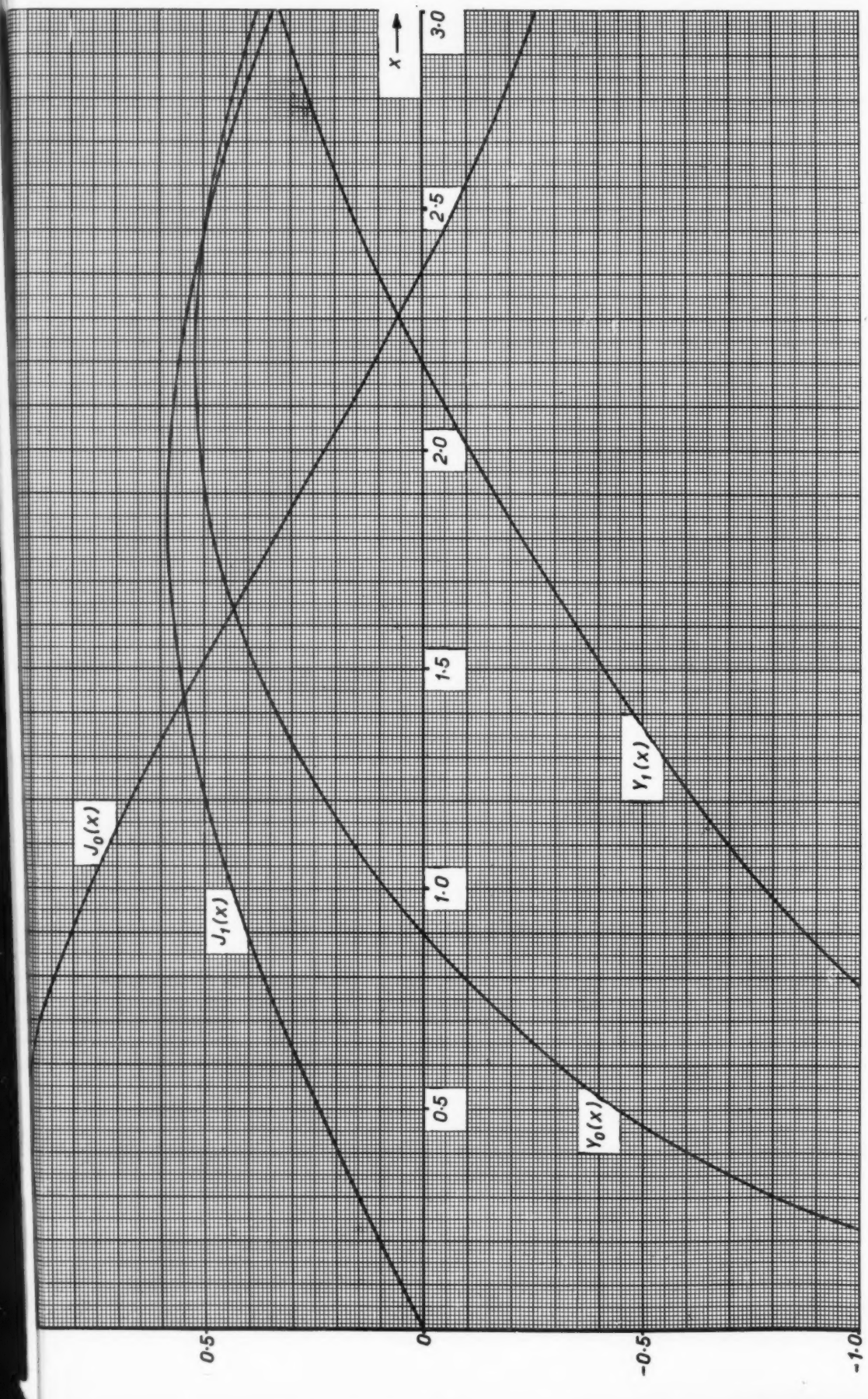
$$\alpha_Z = \pi/2 = 1{\cdot}571 \tag{7.64}$$

so that the overall maximum to average flux $\alpha_R \, \alpha_Z$ for the bare cylinder is

$$\alpha_R \, \alpha_Z = 2{\cdot}316 \times 1{\cdot}571 = 3{\cdot}64 \tag{7.65}$$

For plots of Bessel functions see Data Sheet opposite

Next month's instalment will deal with the effect of a reflector on the critical size.


x
3·0
2·5
2·0
1·5
1·0
0·5
$J_0(x)$
$J_1(x)$
$Y_1(x)$
$Y_0(x)$
0·5
0
-0·5
-1·0

Bessel functions

Bessel's equation is

$$x^2\frac{d^2y}{dx^2}+x\frac{dy}{dx}+(x^2-n^2)\,y=0$$

If n is an integer, this has a solution

$$y = A\,J_n(x) + B\,Y_n(x)$$

A and B are arbitrary constants. $J_n(x)$ and $Y_n(x)$ are defined respectively by

$$J_n(x) = \sum_{r=0}^{\infty}\frac{(-1)^r}{r!(n+r)!}\left(\frac{x}{2}\right)^{n+2r}$$

$$\pi Y_n(x) = -\sum_{r=0}^{n-1}\frac{(n-r-1)!}{r!}\left(\frac{x}{2}\right)^{-n+2r}$$

$$+\sum_{r=0}^{\infty}\frac{(-1)^r}{r!(n+r)!}\left\{2\,ln\left(\frac{1}{2}x\right)-\psi(r+1)-\psi(n+r+1)\right\}$$

where

$$\psi(1) = -\gamma \qquad \psi(r+1) = \sum_{s=1}^{r}\frac{1}{s}-\gamma$$

$$\gamma = 0{\cdot}57721566\ldots$$

Properties of the functions $J_n(x)$ and $Y_n(x)$

$$J_0(0) = 1$$
$$J_n(0) = 0 \qquad n \neq 0$$
$$Y_n(0) = -\infty$$

If $x \ll 1$

$$J_0(x) \simeq 1-\frac{x^2}{4}$$

$$J_n(x) \simeq \frac{1}{n!}\left(\frac{x}{2}\right)^n \qquad n \neq o$$

$$Y_0(x) \simeq -\frac{2}{\pi}\,ln\,\frac{2}{x}$$

$$Y_n(x) \simeq -\frac{(n-1)!}{\pi}\left(\frac{2}{x}\right)^n \qquad n \neq o$$

Recurrence formulae

$$J_{n-1}(x) + J_{n+1}(x) = \frac{2n}{x}\,J_n(x)$$

$$J_{n-1}(x) - J_{n+1}(x) = 2\,J_n'(x)$$

$$n\,J_n(x) + x\,J_n'(x) = x\,J_{n-1}(x)$$

$$n\,J_n(x) - x\,J_n'(x) = xJ_{n+1}(x)$$

A similar set of relationships also hold for the Y functions.

The dashes denote differentiation with respect to x.

Consequences of the above relations are that

$$J_0'(x) = -J_1(x)$$
$$Y_0'(x) = -Y_1(x)$$
$$\int x\,J_0(\alpha x)\,dx = \frac{x}{\alpha}\,J_1(\alpha x)$$
$$\int x\,Y_0(\alpha x)\,dx = \frac{x}{\alpha}\,Y_1(\alpha x)$$

$$Y_{n-1}(x)J_n(x) - Y_n(x)J_{n-1}(x) = \frac{2}{\pi x}$$

and in particular

$$Y_0(x)\,J_1(x) - Y_1(x)\,J_0(x) = \frac{2}{\pi x}$$

$$J_0(2{\cdot}4048\ldots) = 0$$
$$J_1(2{\cdot}4048\ldots) = 0{\cdot}519147\ldots$$

Bessel's modified equation is

$$x^2\frac{d^2y}{dx^2}+x\frac{dy}{dx}-(x^2+n^2)\,y=o$$

If n is an integer this has a solution

$$y = A\,I_n(x) + BK_n(x)$$

A and B are arbitrary constants. $I_n(x)$ and $K_n(x)$ are defined respectively by

$$I_n(x) = \sum_{r=0}^{\infty}\frac{1}{r!\,(n+r)!}\left(\frac{2}{x}\right)^{n+2r}$$

$$K_n(x) = \frac{1}{2}\sum_{r=0}^{n-1}\frac{(-1)^r\,(n-r-1)!}{r!}\left(\frac{x}{2}\right)^{-n+2r}$$

$$(-1)^{n+1}\sum_{r=0}^{\infty}\frac{1}{r!\,(n+r)}\left(\frac{x}{2}\right)^{n+2r}\left\{ln\left(\frac{1}{2}x\right)\right.$$

$$\left.-\frac{1}{2}\,\psi(r+1)-\frac{1}{2}\psi(n+r+1)\right\}$$

Properties of the functions $I_n(x)$ and $K_n(x)$

$$I_0(0) = 1$$
$$I_n(0) = 0 \qquad n \neq 0$$
$$K_n(0) = \infty$$

similar set of relationships also hold for the Y functions.

e dashes denote differentiation with respect to x.

nsequences of the above relations are that

$$J_0'(x) = -J_1(x)$$
$$Y_0'(x) = -Y_1(x)$$
$$\int x J_0(\alpha x)\, dx = \frac{x}{\alpha} J_1(\alpha x)$$
$$\int x Y_0(\alpha x)\, dx = \frac{x}{\alpha} Y_1(\alpha x)$$
$$J_{n-1}(x) J_n(x) - Y_n(x) J_{n-1}(x) = \frac{2}{\pi x}$$

d in particular

$$Y_0(x) J_1(x) - Y_1(x) J_0(x) = \frac{2}{\pi x}$$
$$J_0(2{\cdot}4048\ldots) = 0$$
$$J_1(2{\cdot}4048\ldots) = 0{\cdot}519147\ldots$$

essel's modified equation is

$$x^2 \frac{d^2y}{dx^2} + x\frac{dy}{dx} - (x^2 + n^2)\, y = o$$

n is an integer this has a solution

$$y = A I_n(x) + B K_n(x)$$

and B are arbitrary constants. $I_n(x)$ and $K_n(x)$ are efined respectively by

$$I_n(x) = \sum_{r=o}^{\infty} \frac{1}{r!\,(n+r)!} \left(\frac{2}{x}\right)^{n+2r}$$

$$K_n(x) = \frac{1}{2} \sum_{r=o}^{n-1} \frac{(-1)^r\ (n-r-1)!}{r!} \left(\frac{x}{2}\right)^{-n+2r}$$

$$(-1)^{n+1} \sum_{r=o}^{\infty} \frac{1}{r!\,(n+r)} \left(\frac{x}{2}\right)^{n+2r} \left\{ ln\left(\frac{1}{2}x\right) \right.$$

$$\left. -\frac{1}{2}\ \psi(r+1)\ -\frac{1}{2}\psi(n+r+1) \right\}$$

roperties of the functions $I_n(x)$ and $K_n(x)$

$$I_0(0) = 1$$
$$I_n(0) = 0 \qquad n \neq 0$$
$$K_n(0) = \infty$$

Nuclear Power
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DATA SHEET 4

Bessel functions

In calculating the critical size of reactors, a useful method of solution involves the employment of Bessel functions. Here the basic formulæ are summarised in convenient form and graphs of Bessel functions of the first and second kind are provided

If $x \ll 1$

$$I_0(x) \simeq 1 + \frac{x^2}{4}$$

$$I_n(x) \simeq \frac{1}{n!}\left(\frac{x}{2}\right)^n \qquad n \neq o$$

$$K_0(x) \simeq ln\,\frac{2}{x}$$

$$K_n(x) \simeq \frac{1}{2}\,(n-1)!\,\left(\frac{2}{x}\right)^n \qquad n \neq o$$

Recurrence formulae

$$I_{n-1}(x) - I_{n+1}(x) = \frac{2n}{x}\,I_n(x)$$

$$I_{n-1}(x) + I_{n+1}(x) = 2\,I_n'(x)$$

$$nI_n(x) + x\,I_n'(x) = x\,I_{n-1}(x)$$

$$n\,I_n(x) - x\,I_n'(x) = -x\,I_{n+1}(x)$$

For the K functions the signs on the right-hand sides of the formulae are to be reversed.

$$I_0'(x) = I_1(x)$$

$$K_0'(x) = -K_1(x)$$

$$\int x\,I_0(\alpha x)\,dx = \frac{x}{\alpha}\,I_1(dx)$$

$$\int x\,K_0(\alpha x)\,dx = \frac{x}{\alpha}\,I_1(\alpha x)$$

$$K_{n-1}(x)\,I_n(x) + K_n(x)\,I_{n-1}(x) = \frac{1}{x}$$

and in particular

$$K_0(x)\,I_1(x) + K_1(x)\,I_0(x) = \frac{1}{x}$$

Asymptotic expansions

For x large and positive

$$I_0(x) \sim \frac{e^x}{(2\pi x)^{\frac{1}{2}}}\left\{1 + \frac{1^2}{1!8x} + \frac{1^2\,3^2}{2!(8x)^2} + \frac{1^2\,3^2\,5^2}{3!(8x)^3} + \ldots\right\}$$

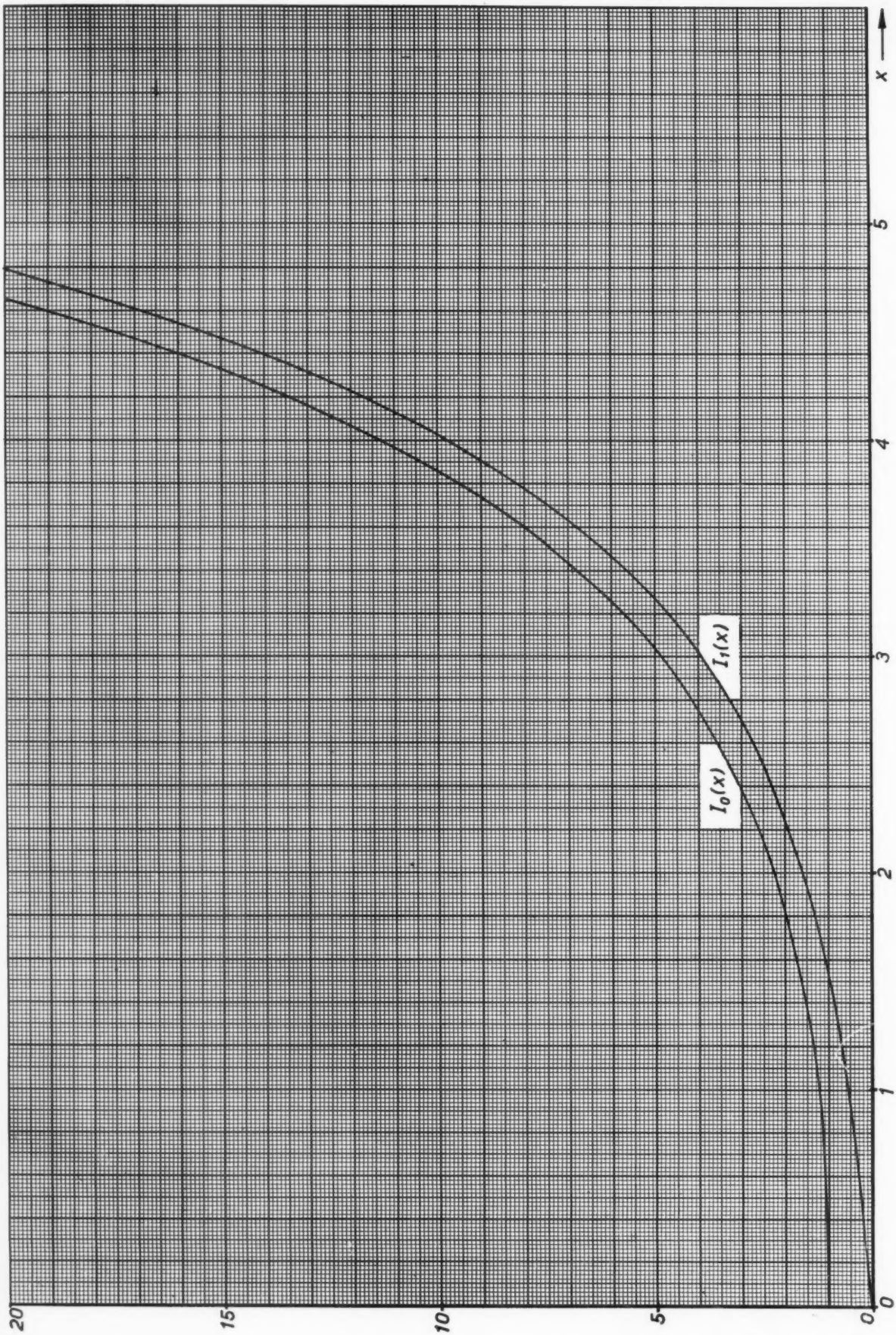
$$I_1(x) \sim \frac{e^x}{(2\pi x)^{\frac{1}{2}}}\left\{1 - \frac{1.3}{1!8x} - \frac{1^2\,3.5}{2!(8x)^2} - \frac{1^2 3^2 5.7}{3!(8x)^3} - \ldots\right\}$$

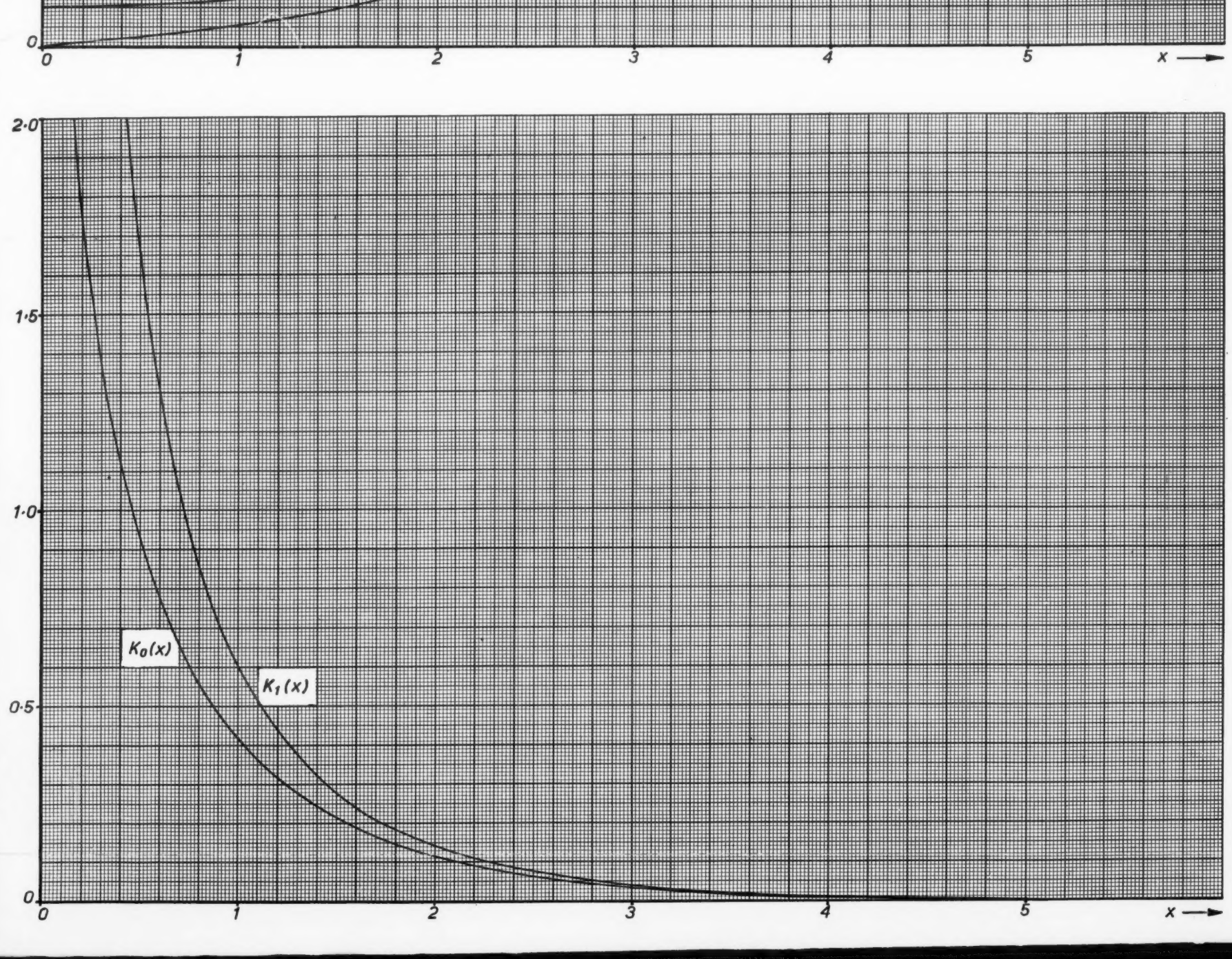
$$K_0(x) \sim \left(\frac{\pi}{2x}\right)^{\frac{1}{2}}e^{-x}\left\{1 - \frac{1^2}{1!8x} + \frac{1^2\,3^2}{2!(8x)^2} - \frac{1^2 3^2 5^2}{3!(8x)^3} + \ldots\right\}$$

$$K_1(x) \sim \left(\frac{\pi}{2x}\right)^{\frac{1}{2}}e^{-x}\left\{1 + \frac{1.3}{1!8x} - \frac{1^2\,3.5}{2!(8x)^2} + \frac{1^2 3^2 5.7}{3!(8x)^3} - \ldots\right\}$$

Modified Bessel functions over

Modified Bessel functions of the first kind

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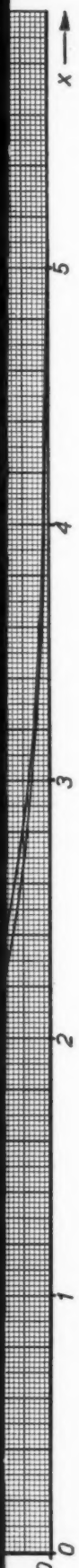

Referenc

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$K_1(x)$.

Tables of
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This also give
comprehensiv

References

British Association Mathematical Tables VI: Bessel Functions. Part I. Cambridge University Press

This gives values of $J_0(x)$, $J_1(x)$, $Y_0(x)$, $Y_1(x)$, $I_0(x)$, $I_1(x)$, $K_0(x)$, $K_1(x)$.

Tables of Functions: Jahnke and Emde, Dover Publications.

This also gives tables of the above Bessel functions but is much less comprehensive than the British Association Tables.

TI research centre at Walsall

A total of 100 miles of alloy steel tube for Calder Hall was supplied by companies in the Steel Tube Division of Tube Investments Ltd according to chairman Sir Ivan Stedeford in his annual report to TI shareholders. Sir Ivan said that events alone would tell what TI's future contributions will be to these great nuclear developments, but their demands upon industry—on plant, staff, research and finance alike—were bound to be heavy. He felt confident that TI products would earn as integral a place in the power and propulsion systems of the future as they have done in those of the past.

Sir Ivan who, it will be recalled, is also a part-time member of the UKAEA, said that his group was convinced of the value of long-range scientific research and it is interesting to note that Sir Ben Lockspeiser, formerly DSIR secretary, recently joined TI's board. The group's technological resources are being concentrated in a new Centre at Walsall airport and four sections—Control Engineering, Nuclear Engineering, Plastics Development, and Data Handling and Computing are already there.

Swiss reactor contract for IDL

The Swiss P34 materials testing reactor to be built by Reaktor AG will have some British instrumentation. Isotope Developments Ltd announced last month that they are acting as consultants to Landis and Gyr AG for the instrumentation of the reactor. IDL will be responsible for the recommendation and supply of the full nucleonic instrumentation which includes the channels for control and safeguarding the reactor and its surroundings. The contract was won against stiff competition from America and adds another reactor contract to IDL's already extensive order book for instrumentation for AEI-JT *Merlins*—several of which are now on order.

P34 is a natural uranium, heavy-water moderated reactor and is to be built at Würenlingen. It is due for operation at the beginning of 1959.

Plessey office in Holland

To supervise Group interests in northern and central Europe, Plessey International Ltd has set up an office at Singel 160 Amsterdam C. As Territory Manager is E. A. Springett who has been Plessey's representative in this part of the world for some years. He is responsible for all sales matters.

The Plessey Group is one of the leading British manufacturers of electronic, nucleonic aircraft and automation equipment and Plessey International is the Group's overseas marketing organization.

New mill at Kayser, Ellison

A new 10½ in. double-duo rolling mill was recently installed at the Sheffield works of Kayser, Ellison and Co Ltd. The four-stand mill was supplied by The Brightside Foundry and Engineering Co Ltd of Sheffield and rolls sizes from ¼in. to 1⅜in. dia as well as sections and flats up to 2½in. wide. The mill is driven by a 500 hp GEC d.c. motor with a speed range 375—750 rev/min, supplied from a 413kW mercury arc rectifier. For heating the billets, a gas-fired, continuous pusher type furnace is installed.

This is just part of a considerable expansion programme at present being undertaken by KE. Recently, a 10-ton arc furnace enlarged their steel-making capacity: a new 800-ton press provided relief in the heavy cogging and forging sections; and a new three-high 14in. mill helped to solve the shortage of lighter cogging and rolling facilities for larger sizes. Work is now in progress to double the size of the heat-treatment department and to build a new chipping and grinding shop. Further ahead is a project to expand and modernize the annealing and wire department.

Kayser, Ellison say they are one of the few steelmakers in Britain who can produce in their own plant anything from ingots to cold drawn wire a few thous in diameter.

Advice on flexible pipes

A new and enlarged *London Flexible Centre* of the Compoflex Co Ltd was opened recently at 23–25 Northumberland Avenue WC2, by Sir Norman Kipping, director-general of the Federation of British Industries. Sir Norman said that Compoflex were dealing with a highly specialized and important component which had to cope with temperature, pressure, corrosion, flexibility and all the other properties of a tube. In selecting flexible tubing, too many people were guided by price alone said Sir Norman, and he felt that value for money rather than cheapness was the aim.

The old *Centre* at Grovenor Gardens, set up in 1952, had now become too small and the new premises and showrooms were necessary. The ground floor of the 3-storey building is given over to the *Centre* and here are displayed a comprehensive exhibition of all types of flexible pipes and hoses. A complete advisory service is available. Sir Norman also announced the first issue of a new quarterly house-journal *Arteries of Industry*.

BOE School opened

A new craft training school for 45–50 apprentices employed by British Oxygen Engineering Ltd was opened last month in Edmonton, London by Robert Carr MP, Parliamentary Secretary to the Ministry of Labour.

Completed in nine months at a cost of £26,000 the school comprises machine shop, fitting sections and a lecture room, and the apprentices are given instruction in plant, industrial, medical and aircraft applications. The School can also be used for intensive courses for the upgrading of fitters, machinists and inspectors and also for the teaching of new techniques to staff in general.

EMI Electronics Exhibition

More than a hundred products—many of them new and on view for the first time—were shown in both static and operating displays in an exhibition held last month in London by E.M.I. Electronics Ltd. The exhibits included twelve measuring oscilloscopes of four different types fed from various inputs and performing functions illustrating the versatility of these instruments. There was also a section on special valves and tubes which included a new miniature photomultiplier tube and the Z319 electron-multiplier valve.

In Brief

Racal Engineering Ltd have appointed Farnell Instruments Ltd of Hereford House, North Court, Vicar Lane, Leeds 2 (Leeds 32958) sole distributors for their range of digital counters and frequency meters in the North of England area. Farnell Instruments are fully qualified to discuss any special application of these equipments and their technical staff is being trained in the servicing of these Racal products.

Humphreys & Glasgow (Canada) Ltd has been incorporated as an associate of Humphreys and Glasgow Ltd of London, the well-known gas, petroleum, chemical and process engineers. Address of new company is: 837 Eglinton Avenue, West Toronto 10, Ontario. Vice-president Peter de Gray is in charge of sales, Vice-president C. T. Hawkes, of engineering.

General Metal Utilisation Co Ltd have moved their Crewe office to: 27 Manor Street, Manchester 12 (ARD 6987).

INSTITUTIONS

Industrialists praise Calder

Experience in building Calder Hall has shown that Britain can now construct nuclear power stations to a known time scale, to a fixed cost and to give the performance the designers calculated. This was stated by Richard V. Moore, chief engineer of Calder Hall, in his address to the opening session of the symposium held by the British Nuclear Energy Conference in London on Nov 22. Previously, the audience of about 1000 had heard Sir Christopher Hinton say that we would probably still be building some gas-cooled reactors 25 years from now, although by then, advanced types will probably be superseding them.

Speaking after Mr Moore's speech, leading British industrialists added their praise to the achievement of Calder Hall. Sir George Nelson, English Electric chairman, said it was a thrilling and inspiring story. He was particularly impressed with the skilful costing and with the way the many problems had been solved, not just in isolation but in conjunction with many others.

Mr. Harry West, managing director of the AEI-John Thompson Nuclear Energy Co Ltd, said the world was waiting the results of the tendering for the first CEA stations with the greatest interest. He said that Harwell's new Dido was also a great achievement but felt that industry had now reached the stage where they badly needed a materials testing reactor of very high flux. This was beyond the resources of any one group and Mr West put forward a plea for the AEA to take the lead in providing one, in cooperation with industry. He said that Britain must make a determined attack on the export market with small reactors. This would need enriched fuel and the problem of availability must be solved before substantial progress could be made. He was particularly interested in the VHT reactor to which Mr Moore would be referring later.

From the GEC Simon-Carves group, managing director Arnold Lindley said that improvements in the steam side were not likely to be spectacular but this was not true of the nuclear aspect. In his opinion, we ought to build the biggest reactors possible—in this way the unit cost would come down. To obtain the highest possible load factor, fuel charging must be completely automatic and reactors built with full regard for maintenance. It had been said (Mr Butler at Calder Hall, ed.) that by 1965 all our new power stations would be nuclear. This meant that the whole of British industry must look ahead now. For example, certain kinds of steel were still in very short supply and Mr Lindley declared that in some classes there is not enough to carry out the present plans. He also considered that there must be tremendous effort made to obtain and train the many engineers and scientists that would be needed.

Sir Claude Gibb, Nuclear Power Plant Co Ltd chairman, said the present conference made a great contribution not only to knowledge but to human welfare: it would go down in history as one of the most important ever held. While some countries had been talking, Britain had been doing. But we were not resting and the new designs would already show a great advance on Calder Hall. Industry, asserted Sir Claude, was ready for action now and he thought that a message should go to the Minister of Fuel and Power asking—in the words of Sir Winston Churchill's famous wartime notes to his department chiefs—for 'action this day.'

Afterwards, the symposium got down to presentation and discussion of the 19 papers it had before it.

New standard for source holders

The British Standards Institution recently issued a standard for gamma-ray source capsules for industrial radiography (BS2783:1956). This was evolved in close collaboration with Harwell and the Radiochemical Centre. It deals with two designs of cylindrical capsules, about 1 in. long for the convenient holding of radioisotopes other than radon, and for radon respectively. The activated material is in the form of a small cylinder which is placed within the capsule, the open end being then sealed. The tongue of the capsule is furnished with notches of specified dimensions which form a positive grip for the spring clips fitted in source holders. The two capsules have been so designed in respect of their overall dimensions and the form and position of the notch that one type of holder and one type of gamma-ray source container may be used with either form of capsule. In the case of the non-radon capsule a space on the tongue is provided on which an identification symbol may be stamped; this design was originally evolved by the AERE. In both types of capsule the notches on the tongue form the datum for the location of the centre line of the source after it has been sealed in the capsule.

The specification gives fully dimensioned drawings of the two capsules and, in the case of the non-radon capsules a series of dimensions is given which provides for the use of sources from 2 x 2 mm. or smaller, up to 6 x 6 mm. Whilst the standard is primarily a dimensional one, some notes are included as to suitable alloys for the manufacture of the two types of capsules.

Copies: the British Standards Institution, 2 Park Street, London W1, price 2s 6d.

What makes a reactor incident

Two characteristics of nuclear power plant provide most of the operating hazards: the large inbuilt reactivity which if released in an uncontrolled manner results in a very high rate of power rise, and the high rates of heat release from reactor cores—many times those prevailing in other thermal machinery. This was the main conclusion in a paper read to a joint meeting of the Institute of Marine Engineers and the Institution of Naval Architects in London on Nov 27 by Mr C. D. Boadle who is in charge of the engineering laboratory in the Nuclear Engineering Section of the Rolls-Royce Ltd, Derby.

Mr Boadle's paper formed a general introduction to the subject and he dealt with the factors determining the characteristics of reactors under steady and transient conditions. He accepted the thesis that no plant can be absolutely safe and that the probability of an accident must be reduced to a small but finite value by taking a calculated but acceptable risk. As experience is gained, the risk will decrease. Mr Boadle thought that for many types of reactor, complete containment in a gas tight pressure shell might be necessary. Homogeneous systems, Mr Boadle concluded, would offer substantial rewards in terms of safety as they provide a method of dispensing with the need for a large amount of reactivity, at the same time providing substantial stabilizing temperature effects.

Regular Physics Conferences

The Physical Society is to hold regular meetings on nuclear physics two or three times a year. The purpose of these is to provide a stimulus for younger physicists to meet workers in allied fields and to report on their work. The first meeting is to be held at Harwell on Jan 16–17, 1957. Later, meetings will be held at various universities.

The Harwell meeting will take place in five 3-hr sessions (two in parallel). Fuller details are expected early in December.

Chemicals move house

The Institution of Chemical Engineers have moved to a new address at: 16 Belgrave Square, London SW1 (telephone: BELgravia 3647; telegrams: Inchemengs, Knights, London).

RESEARCH REPORTS

*The following reports have been made available to the public by the United Kingdom Atomic Energy Authority. They may be borrowed or photocopies obtained from the Science Library, London, and the Central Libraries at Acton, Birmingham, Bristol, Glasgow, Kingston-upon-Hull, Liverpool, Manchester, Newcastle-upon-Tyne and Sheffield. They are are also deposited in the Copyright Libraries (i.e. British Museum; University Library, Cambridge; Radcliffe Science Library, Oxford; National Library of Scotland, Edinburgh) and in the Patent Office Library. Reports marked * may be purchased from Her Majesty's Stationery Office.*

Reports are also available in the United States through certain depository libraries listed in Nuclear Science Abstracts, or direct from Technical Information Service, Oak Ridge National Laboratory, Oak Ridge, Tenn.

Atomic Energy Research Estabt.

A preliminary report on the determination of submicrogram quantities of individual rare earths by radioactivation using ion exchange separation. F. W. Cornish (Sept 4, 1953. 47 pp) 7s 6d. AERE-C/R 1224*

The diffusion theory of fine structure in thermal neutron reactor assemblies consisting of cylindrical fuel elements set in a square lattice array. A. C. Clark, D. A. Newmarch. (Apr 18, 1955. 20 pp) 3s. AERE-RP/R 1657*

A preliminary investigation of shocks in a curved channel. R. Hide, W. Millar. (June, 1956. 22 pp) AERE-GP/R 1918*

The effect of removing plate fuel elements upon the thermal neutron fine structure in reactor assemblies. Pt. 1. D. A. Newmarch. (July, 1956. 14 pp) AERE-R/R 1940

Neutron distribution in the air spaced core assembly of ZEPHYR. J. E. R. Holmes, M. U. Curry, M. Waldegrave. (June, 1956. 39 pp) AERE-R/R 1949*

A nuclear resonance detector and magnetic field stabiliser. D. A. Gray. (July, 1956. 17 pp) 2s 9d. AERE-GP/R 1967*

Free convection in heat generating fluid (laminar flow). Pt. 2. Negative temperature gradient. J. Woodrow. (July, 1956. 22 pp) AERE-R/R 1981

The effect of neutron irradiation on the mechanical properties of metals. Pt. 1. Titanium and zirconium. M. J. Makin, F. J. Minter. (July, 1956. 20 pp) AERE-M/R 2009

Radiostrontium fallout in biological materials in Britain R. J. Bryant, A. C. Chamberlain, A. Morgan, G. S. Spicer. (Sept 5, 1956, 60 pp) AERE-HP/R 2056

Preliminary experiments on the rheology of thoria slurries H. A. Kearsey. (1956. 7 pp) AERE-CE/M 186

Industrial Group

Determination of combined nitrogen in molybdenum metal (modified Allen method). (July 18, 1956) IGO-AM/S 43

Design and development of a variable-flow centrifugal pump for alkaline solutions. A. Barker, F. McKay. (Aug 23, 1956. 7 pp) IGR-R/CA 184

A fifty-four channel recorder. E. Duncombe, W. Jaques. (Aug 22, 1956. 17 pp) IGR-R/CA 188

Transformation hysteresis in uranium—1/2 At.% molybdenum alloy. R. Doldon. (Sept 25, 1956. 8 pp) IGR-TN/C 370

PROGRAMME

ICE Institution of Civil Engineers. IMechE Institution of Mechanical Engineers. IEE Institution of Electrical Engineers. IChemE Institution of Chemical Engineers. IP Institute of Physics. PS Physical Society. SCI Society of Chemical Industry. IM Institute of Metals. IMet Institution of Metallurgists. IMM Institution of Mining and Metallurgy. IPE Incorporated Plant Engineers. SIT Society of Instrument Technology.

November

Thu 29 **Bristol** IEE *Nuclear energy in the service of man* Dr T. E. Allibone. 6.30 at Colston Hall
Chelmsford IMechE *Application of atomic energy to power production* S. C. Curran. 7.30 at Hoffman Hall

Fri 30 **London** PS *Discovery of V-particles and the properties of hyperons* Prof G. D. Rochester and Dr C. C. Butler. 5.00 at Science Museum
London IMechE *American system of education and training of mechanical engineers* H. S. Arms. *Education of engineers in Europe* Prof S. J. Davies. 6.00 at Institution

December

Mon 3 **London** IEE *Nucleonic devices in automation*—informal talk by Denis Taylor. 5.30 at the Institution
London SCheml *Elementary particles of nature* Prof P. M. S. Blackett. 6.30 at 14 Belgrave Square SW1

Tue 4 **Chester** IChemE *Centrifugation as a unit operation.* 7.15 at Birkenhead Technical College

Wed 5 **Manchester** IEE *Junction and point-contact transistor scaling circuits* G. B. B. Chaplin and A. R. Owens. 6.45 at Engineers Club
Loughborough IMechE *Nuclear reactor fundamentals* B. L. Goodlet. 7.00 at Lecture Theatre College of Technology
Manchester IM *Boron in Steel* F. B. Pickering. 6.30 at the Central Library

Fri 7 **London** IMechI *The self-excited vibrations of axial flow compressor blades.* A. D. S. Carter and D. A. Kilpatrick. 6.00 at the Institution
Peterborough IPlantE *Control of loads on the grid.* 7.30 at White Lion Hotel

Mon 10 **Chester** IEE *Control of nuclear reactors* R. J. Cox and J. Walker. 6.30 at Town Hall
Newcastle IEE *Conduction and induction pumps for liquid metals.* L. R. Blake. 6.15 at Neville Hall

Wed 12 **Sheffield** IEE *Pimlico district heating—costs and financial results* B. Donkin *et al.* 6.30 at Grand Hotel
Birmingham IChemE *Heat transfer and pressure drop in packed beds* Prof. F. Garner *et al.* 6.30 at Midlands Institute, Paradise Street

Fri 14 **London** IMechE *The draft code of practice for acceptance tests on steam turbine installations.* Steam group discussion. 6.45 at the Institution

Mon 17 **Edinburgh** PS *Beta and gamma spectroscopy and related topics.* Three day autumn meeting at The Department of Natural Philosophy, The University

Thu 20 **London** IMM *Rapid estimation of oxides of niobium and tantalum in black sand concentrates* M. C. Curwen. 5.00 at Geological Society, Burlington House
Blackburn IPlantE *Feedwater treatment* D. Warburton. 7.30 at Golden Lion Hotel

NAMES IN THE NEWS

Dr J. F. Loutit director of the Harwell radio-biological research unit was presented with one of the $1000 Robert Roesier de Villiers awards of the Leukemia Society in New York on Nov 7

Dr A. M. Uttley has been appointed superintendent of the control mechanisms and electronics division of the National Physical Laboratory, Teddington

Lord Forteviot and **Mr G. F. Ashford** have been appointed directors of The Distillers Co Ltd.

Mr J. Samuels has joined the board of Winston Electronics. He joined the company in 1954 as chief buyer

Mr H. F. Bibby has been made assistant general manager of Metropolitan-Vickers Electrical Export Co Ltd. He was previously Manager, American Division

Mr. Norman McKinnon-Wood managing director of Griffin and George Ltd, chairman of the British Laboratory Ware Association is on a visit to the United States

Mr R. W. Boughton has been appointed sales manager of Fleming Radio (Developments) Ltd of Stevenage

Capt F. S. Bell RN (ret) has taken up an executive appointment with Pollard Bearings Ltd, Ferrybridge, Yorks.

Mr M. C. Blythe has been appointed sales director of Doulton Industrial Porcelains Ltd.

Mr C. T. Hinchliffe and **Mr W. B. Knowles** have joined the sales engineering staff of Brook Motors Ltd, Sheffield

Mr. W. G. Martin has been appointed deputy overseas manager of A. Reyrolle & Co Ltd, Hebburn, Co Durham

Mr C. E. Chapman and **Mr E. J. Phillipson** have joined the technical sales staff of Acheson Colloids Ltd, London

Mr A. G. Stewart chairman and managing director of Stewarts and Lloyds Ltd has been appointed a part-time member of the Iron and Steel Board

BOOKS

Proceedings of the symposium on the physics of fission held at Chalk River, Ontario, May 14-18, 1956 Edited by G. C. Hanna, J. C. D. Milton, W. T. Sharp, N. M. Stevens, and E. A. Taylor. AECL 329

This is an edited version of some twenty papers read at the symposium. The authors include G. C. Hanna, J. C. D. Milton, J. S. Fraser, H. G. Thode, J. D. Jackson, H. E. Gove and H. McManus. Most of the papers take the form of summaries of recent work on different aspects of the subject, both experimental and theoretical, and together with the bibliographies form a fairly comprehensive review of fission physics as it stands today. Possibly because of the lack of a really satisfactory theory of fission, this is a branch of physics in which there has been rather a paucity of survey articles, and the present volume is therefore very welcome. That the time is ripe for a publication of this kind may be seen from the fact that this report contains references to some two hundred papers published since Whitehouse's 1952 review.

The subject matter includes the probability of fission induced by slow neutrons, neutrons of a few MeV, and gamma-rays; spontaneous fission; fission by very high energy particles (including the recent Russian work using nuclear emulsions); the mass, charge, kinetic energy and angular distribution of fission fragments; the emission of neutrons and gamma-rays; fission thresholds and barriers; the liquid drop model, the statistical theory and the collective model.

As one might expect, there is a certain amount of repetition between the different authors, and because of the limited time for the papers some of the subjects are treated rather sketchily. The great merit of this report is in defining the limitations of present experimental knowledge and theoretical interpretation, and it should provide a stimulus for workers in both fields. An agreeable feature is the considerable amount of space devoted to theoretical considerations, even if these are of a tentative nature; no less important are the discussions following the papers, in which the different points of view are thrashed out. Incidentally, editors of similar reports might well take note of the careful editing of these discussions to remove unimportant remarks but retain the essential arguments. For a duplicated document the text and diagrams (of which there are many) are unusually clear; the editing is excellent throughout.

G. N. Harding

Electrostatic precipitation in theory and practice by H E. Rose and A. J. Wood. 5½ in. × 8 in. 166 pp. London 1956: Constable. Price 17s 6d.

The publication of this volume is most welcome since, as Professor Andreason of the Royal Technical University, Copenhagen, mentions in his foreword, there is no other readily-available book on this subject. The authors point out that the design of electrostatic precipitators for industry has largely been based on purely empirical data accumulated by manufacturers and operators and, in their clear exposition of existing theory, they show that much of this does not agree with practice. Especially is this difference shown by the fact that precipitator efficiencies as calculated from the usually accepted equation of Deutch give results about twice as great as the measured values obtainable with practical installations. Considering the variation in size of particles found in practice, the authors show that the only way in which the performance of a unit, operating under normal conditions, can be accurately assessed is by comparison of the size-frequency curve for the material leaving the precipitator with that for the material entering the precipitator. The problems associated with precipitator design, construction and operation are also dealt with thoroughly, as well as the important question of the high voltage power supplies required. In an otherwise admirable survey of existing knowledge, one slight criticism might be the brief mention given to the precipitation of radioactive aerosols. Smith, *Industrial Chemist, Dec 1955*, has pointed out that re-entrainment is particularly serious with radioactive particles in an electrostatic precipitator, and may prove a serious obstacle to its use independently of filters. In view of the fact that the authors mention their continuing research into the problems of electrostatic precipitation we may look forward to a discussion of this particular problem in future editions.

Denis Aliaga-Kelly

Nuclear and Radiochemistry G. Friedlander and J. W. Kennedy. John Wiley & Sons Inc, New York. Price $7.50. Chapman and Hall, Ltd, London. Price £3

There must be few indeed amongst the radiochemical fraternity, especially on the teaching side, who have not during the past few years drawn heavily on the fund of information contained in Friedlander and Kennedy's *Introduction to Radiochemistry*. It is a revealing commentary on the speed of development of the subject, and by no means an adverse reflection on the earlier edition, that it is necessary after so relatively short a period of time to produce a second version with a new title, and with approximately 65 per cent of the material appearing in it for the first time.

Since the earlier edition, such techniques as scintillation counting, proportional counting, and pulse-height analysis have passed from the development stage to application as a routine tool in the radiochemical laboratory, and are now given an appropriately extended discussion. Apart from these and other developments in measuring techniques there have, of course, been very striking advances in other fields; the study of nuclear systematics has been brought to the state where it is of direct significance to the radiochemist; several new artificially produced elements have been reported; and chemical separation methods have been improved by the introduction of new ion exchange and solvent extraction procedures. All these changes are chronicled in the concise, accurate and readable manner as characteristic of this volume as of its predecessor.

In short, it would be difficult to give too strong a recommendation to this book. Its content and the style of treatment make it an admirable basis for a course of instruction, for which purpose the numerous examples are especially valuable; the only tinge of regret one feels forced to note is that the new price will probably put the book beyond the reach of most undergraduates. In any event, it would seem safe to predict that it will remain for some years an essential handbook for anyone seriously interested in radiochemical methods—until, in fact, fresh advances render a further edition necessary.

G. R. Martin

PUBLICATIONS

Plant construction services Head Wrightson Processes Ltd, Baltic St, London EC1. Describes and illustrates firm's contracts at famous oil refineries and other plants—including DIDO at Harwell

Arteries for industry no 1 Compoflex Co Ltd, 23-25 Northumberland Avenue, London WC2. First of new quarterly from well-known flexible hose manufacturers

Lead in atomic energy Lead Development Association, Eagle House, Jermyn St, London SW1. Useful brochure describing uses of lead as shielding in the form of metal and as lead-glass

Scientific film review Vol 2 No 4 The Scientific Film Association, 164 Shaftesbury Avenue, London WC2. Special issue contains full details of 145 films on atomic energy and related subjects

Holborn Viaduct to Calder Hall Babcock & Wilcox Ltd, Babcock House, Euston Rd, London W1. Fascinating history of electricity supply industry from start in 1882 in London. Illustrated with contemporary prints and photographs

Plessey at Towcester The Plessey Co Ltd, Towcester, Northants. Shows manufacture and application of dust cores, flake cores, ceramic capacitors, microwave absorbers, ceramic insulators, tantalum electrolytic capacitors etc.

Piezoelectric ceramics Technical Ceramics Ltd, Towcester, Northants. Technical data on these materials

Calmet heat-resisting alloy steel The Calorizing Corporation of Great Britain Ltd, Lynton House, 7-12 Tavistock Square, London WC1. Describes 25/12 chrome-nickel cast steel suitable for high temperature applications

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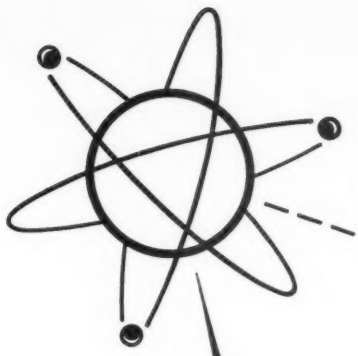

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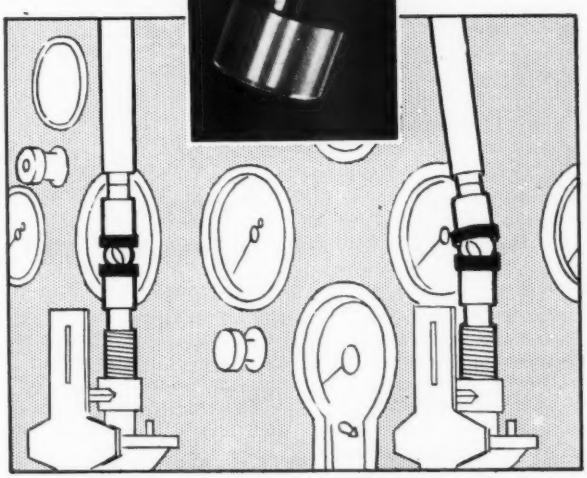

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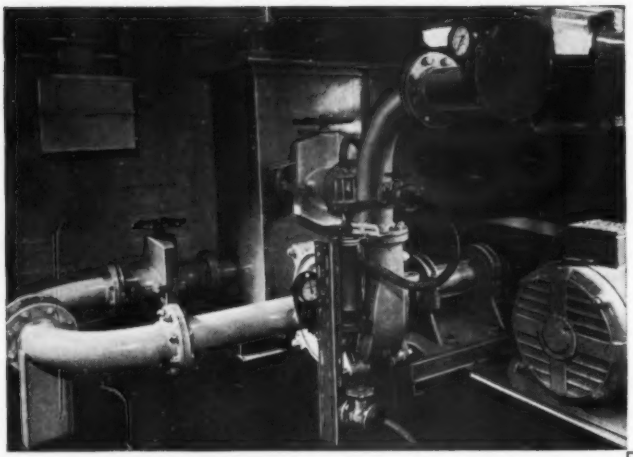

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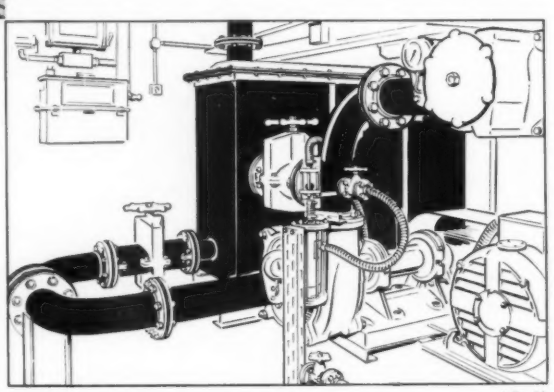

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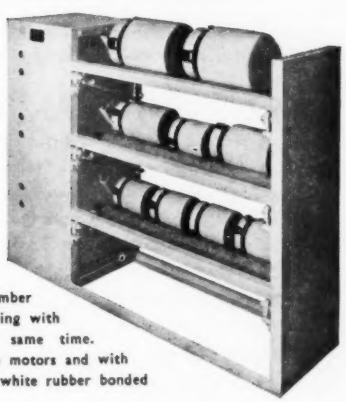

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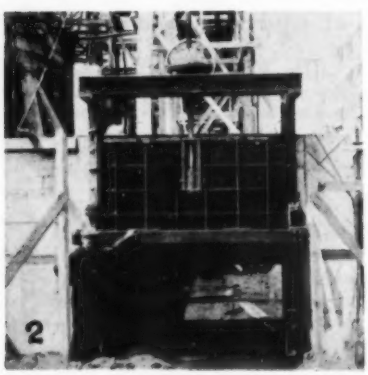

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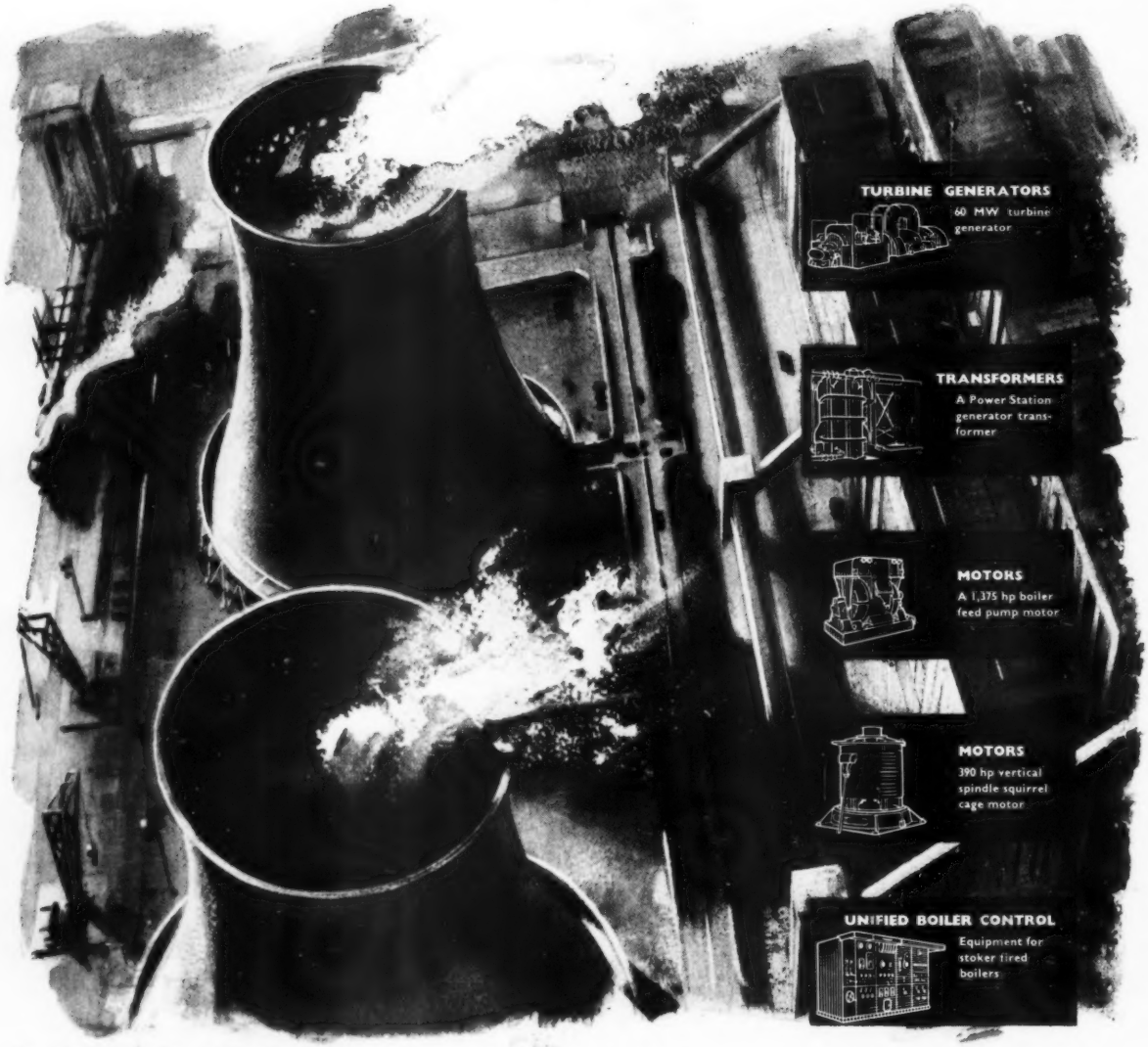

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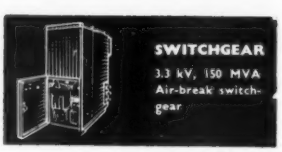

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